SELECTION OF SYSTEMS TO PERFORM EXTRAVEHICULAR ACTIVITIES

Man and Manipulator

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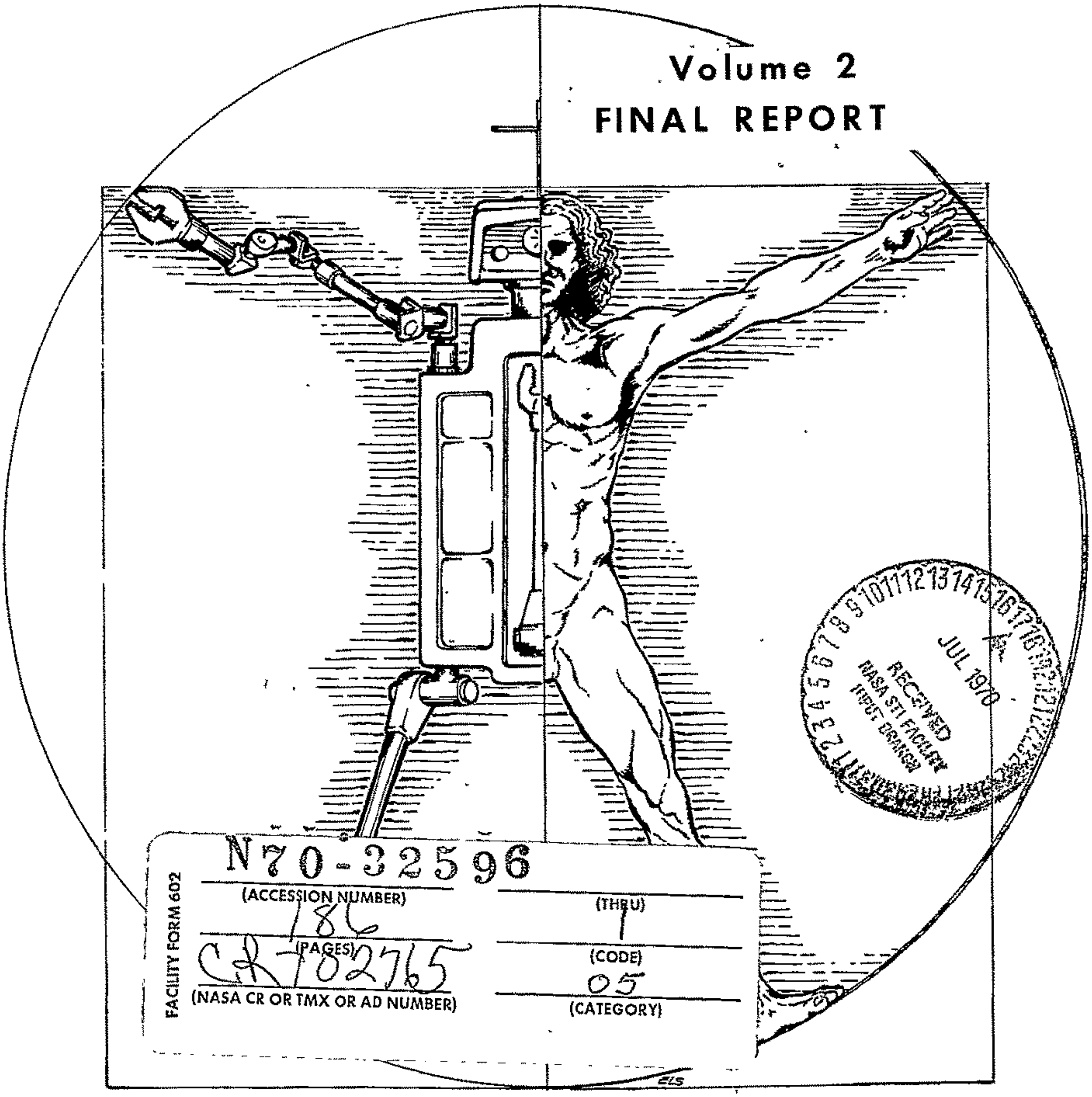
Volume 2

FINAL REPORT



MATRIX RESEARCH
HUMAN FACTORS DIVISION

A URS Systems Affiliate

SELECTION OF SYSTEMS TO PERFORM
EXTRAVEHICULAR ACTIVITIES
Man and Manipulator
Contract No. NAS8-24384

Volume 2 - Final Report

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FOREWORD

The following represents work which was performed on a study of the Man vs. Manipulator Functions and is the Final Report on Contract NAS8-24384, National Aeronautics and Space Administration, Marshall Space Flight Center, Alabama.

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SECTION I

INTRODUCTION

1.0 INTRODUCTION

In future orbital flights, a basic design decision will be whether to employ astronaut EVA to accomplish tasks exterior to the vehicle or to use remote devices. This decision will be based on such factors as crew time availability, weight penalty, costs, safety considerations, and the state of technology of EVA aids and remote devices. With the exception of the current technology status, these considerations are specific to a mission and the operations and systems planned for that mission. The technology refers to the equipment design and procedures required to conduct and support the EVA on remote operations.

This study is comprised of a survey and analysis of technologies for EVA and remote systems in terms of general activities or functions projected for future missions. Capabilities and limitations of candidate systems were developed, and these data are included in a separate design handbook.

The study objectives are:

1) To develop a comprehensive description of the general EVA problem, of applicable design solutions, and of related EVA system performance data.

2) To prepare a guidebook for use by space system designers in selection of manual or mechanical means for performing extravehicular functions.

This report describes the EVA problem, lists EVA functions with associated task and performance requirements, and describes currently available methods for satisfying these requirements. A description of functions is contained in Section 2.0, and available methods are presented in Section 3.0. Task, performance, and equipment requirements and capabilities are presented in Section 4.0 for manual EVA and in Section 5.0 for remote manipulator systems.

The handbook developed in this study contains the compilation of all available EVA task and human performance data as well as a logical methodology for determining the optimal method for performing specific functions. The handbook also includes all worksheets and guidelines required for a system designer to select feasible approaches by performing a preliminary trade-off of the effectiveness and related costs; this methodological approach is contained in Section 6.0. The handbook is described in Section 7.0 of this report.

The EVA technology described in this study was arbitrarily segmented into three phases generally reflecting the state of development of the various systems. These phases include:

- The Operational Phase - equipment and procedures already used and/or evaluated during orbital EVA missions.

- The Design Phase - technology planned for missions approved by NASA and currently in the design and development stages. For manual EVA this phase includes the Apollo Telescope Mount (ATM) mission of the Apollo Applications Program and the Apollo XIV missions.

- The Research Phase - equipment and procedures currently under evaluation or proposed as methods for accomplishing EVA functions. This technology applies to advanced missions (Earth Orbital Space Station) and to undefined missions where an EVA capability is projected by planning personnel.

SECTION II

EXTRAVEHICULAR FUNCTIONS AND REQUIREMENTS

2.0 EXTRAVEHICULAR FUNCTIONS AND REQUIREMENTS

In developing a method for selecting an Extravehicular (EV) system (manual or mechanical), it is necessary to review the EV operations required for all past, present, planned, and proposed orbital space flights. In order to minimize redundancy in the analysis and description of these operations, like operations should be grouped into function classes. For the classification scheme to be worthwhile, each operation must appear in one and only one function class, and all operations assigned to a specific class must have identical performance requirements.

Functions will be identified through an examination of operations conducted on past EVA missions, those planned for missions currently in the design phase, and those projected for advanced missions.

2.1 OPERATIONAL EVA MISSIONS

The orbital missions which have included EVA are Gemini IV, IX, X, XI, and XII, and Apollo IX. A description of each mission in terms of objectives and operations is presented below. These descriptions for Gemini flights are abstracted from the "Summary of Gemini EVA," NASA-S-67-793, 1967. At the time of this writing, sufficient data concerning the Apollo IX EVA were unavailable.

2.1.1 Gemini IV

The primary objective of the fourth Gemini mission was to establish the feasibility of EVA. A secondary objective was to evaluate the performance of a Hand-Held Maneuvering Unit (HHMU) for EVA astronaut translation and attitude control. Significant operations accomplished during the 36-minute EVA included:

- HHMU evaluation
- Umbilical evaluation
- Photography

2.1.2 Gemini IXA

The objective of this mission was the evaluation of the Extravehicular Life Support System (ELSS) and the Air Force Astronaut Maneuvering Unit (AMU). On the basis of astronaut performance, it was concluded that an EVA pilot needs more time for familiarization and evaluation than allocated on this mission, and that more effort was required than predicted from ground simulations. The latter conclusion applied primarily to the AMU preparation task where difficulties in maintaining body position led to excessive workloads on the EVA crewman.

Important operations completed during the 2-hour and 7-minute EVA (hatch opening to hatch closing) were:

- Handrail deployment
- S012 micrometeorite package retrieval
- 16mm camera installation
- Attachment of docking bar mirror
- Umbilical evaluation
- Velcro pad evaluation
- Translation to adapter
- Unstowing of penlights
- Connection of tether hooks
- AMU preparation
- Photography

2.1.3 Gemini X

The primary objective of Gemini X EVA was to retrieve the Experiment S010 micrometeorite collection package from the Gemini-Agena Target Vehicle (GATV). Other objectives were HHMU evaluation and retrieval of the experiment S012

Gemini micrometeorite package from the spacecraft adapter section. The astronaut successfully retrieved the S010 package but discarded the replacement package to avoid the risk of losing the retrieved experiment. While moving around the GATV to the S010 location, the pilot lost his hold of the smooth lip of the docking cone and drifted away from the target vehicle. He used the HHMU to translate back about 15 feet to the spacecraft and then to the target vehicle. In maneuvering around the docking cone, he used the wire bundles and struts behind the cone as handholds and was able to maintain control of body position.

Significant operations completed during the 1-hour and 29-minute EVA included:

- Experiment S013 camera mounting
- Deployment of handrails
- S012 micrometeorite package retrieval from adapter
- Nitrogen quick disconnect
- HHMU utilization
- S010 retrieval
- Photography

2.1.4 Gemini XI

Objectives of Gemini XI EVA were attachment of a 100-foot tether between the spacecraft and the target vehicle and further evaluation of the HHMU. A high energy expenditure level experienced by the EVA astronaut led to early termination of EVA. Astronaut fatigue was assumed to result from the effort required in maintaining body position without adequate restraints and from the lack of fidelity of preflight training simulations.

Significant operations accomplished during the 2-hour and 43-minute EVA included:

- Handrail deployment
- Retrieval of experiment S009
- Mounting of EVA camera
- Attachment of spacecraft/GATV tether
- Film change
- Installation of S013

2.1.5 Gemini XII

The Gemini XII EVA objectives included evaluation of body restraints and workloads, attachment of Gemini/GATV tether, and UV stellar photography. It was concluded that tasks are feasible when restraints are used and rest periods are interspersed in the operational sequence, and that underwater simulation duplicated with high fidelity the actual EVA. Work stations at the adapter and the GATV were used for equipment evaluation. Primary operations completed during the 5-hour and 30-minute EVA were:

- Handrail deployment
- Installation and activation of 16mm camera
- Activation of S010
- Translation to adapter
- Velcro evaluation
- Operation of electrical and fluid quick disconnects
- Evaluation of cutting type tools
- Evaluation of torquing operations
- Evaluation of suit mobility
- Translation to Agena

- Evaluation of portable handholds
- Film change
- Tether attachment
- Photograph

2.2 EVA PLANNED FOR MISSIONS IN THE DESIGN PHASE

The only approved system development activity which will use orbital EVA is the Apollo Applications Program, specifically the Apollo Telescope Mount (ATM) Mission. The objective of this Earth-orbital mission is the acquisition of photographic data on solar activity. The ATM will consist of a canister containing several telescopes and film magazines. The ATM is a portion of the AAP Cluster which also includes the Orbital Workshop (OWS), the Air Lock Module (AM), the Multiple Docking Adapter (MDA), and the Command Module (CM).

Primary astronaut activities during the 28- and 56-day missions consist of controlling the sequencing and activation of picture taking and retrieval and replacement of film magazines. This latter task involves one EVA astronaut translating between the AM hatch and two workstations on the ATM canister, removing and replacing six film magazines, and returning the spent magazines to the hatch. A second EVA astronaut will stand by outside the AM hatch to support the maneuvering astronaut, manage his umbilical, and assist him if necessary. In all, six EVA excursions will be required, each lasting about two and one-half hours.

The sequence of activities to be performed by each EVA crewman include the following:

2.2.1 Maneuvering Astronaut

- Egress AM hatch
- Load film magazine transfer device
- Translate to center work station
- Ingress work station

- Transfer film magazines from hatch to work station
- Activate work station
- Retrieve and replace four film magazines
- Egress work station
- Translate to sun-end work station
- Transfer film magazine storage device
- Retrieve and replace two film magazines
- Translate back to center workstation
- Transfer film back to AM hatch
- Transfer back to AM hatch
- Ingress AM hatch

2.2.2 Stand-by Astronaut

- Manage umbilical of maneuvering astronaut during translation
- Manage transfer of film and storage device
- Stand-by to provide assistance

2.3 EVA PLANNED FOR ADVANCED MISSIONS IN THE RESEARCH PHASE

Advanced missions for which EVA is an essential include the Earth Orbital Space Station (EOSS) and scientific orbital mission of the 1970's. Bell (1969) concluded that the EVA, with its present rate of growth and emphasis, should be a well-established, safe, operational technique by the mid-70's. Exploration, inspection, retrieval of data modules, assembly of structures, servicing, repair, and resupply are broad categories of functions which could require EVA. Bell also states that about one-half of a survey of 1200 experiments proposed through 1980 (with emphasis on the 1971-74 time frame) logically require some EVA to satisfy the overall mission

2.3.1 Earth Orbital Space Station (EOSS) (Martin Presentation at MSFC, October, 1969)

The EOSS candidate experiments which will require EVA for their conduct are (EVA time estimates included):

- 5.12 Remote maneuvering subsatellite (24 hours)
- 5.7 Plasma physics and environmental perturbation (25 hours)
- 5.14 Man Systems integration (200 hours--could be done IVA in unpressurized area)
- 5.24e Maintenance and repair
- 5.24f Logistics and resupply
- 5.24g Manned occupancy and space living facilities
- 5.19 Extended space structure development (time undetermined)
- 5.17 Contamination measurements (219 hours per 180-day mission)
- 5.18 Exposure experiments (208 hours per 180-day mission)
- 5.20 Fluid physics in microgravity (30 hours per 180-day mission)

Primary functions associated with these experiments include:

- Repair
- Refurbishment
- Maintenance
- Collection of samples
- Activation

- Monitoring
- Ingress/egress
- Cargo handling/transfer

The refurbishment of the EOSS will be performed by the Space Shuttle. Ground rules for development of the shuttle state that throughout its operations the crew will be IVA. The primary functions to be performed by the shuttle include:

- Passenger transfer
- Cargo transfer
- Propellant transfer
- Satellite recovery
- Space station personnel rescue

2.3.2 Advanced Scientific Technology Missions

In a comprehensive analysis of extravehicular engineering activities, North American Rockwell (1968) identified the scientific and technical experiments planned for the period 1971-74 which would require EVA. The experiments fall into the following general areas:

- Astronomy
- Bioscience
- Physical Science
- Earth Science
- Meteorology
- Communications/Navigation
- Advanced Technology

- Orbital Operations
- Biomedical/Behavioral

For these areas, 98 separate experiments were identified which would require EVA for their performance.

2.4 DERIVATION OF EXTRAVEHICULAR FUNCTIONS

From an assessment of activities performed or to be performed in free space, external to the prime vehicle or cluster, a series of EV functions were determined. The functions required for each operational, design, and research mission are identified in Table 2-1. Several of these functions can be combined into a single function so that the listing of EV functions is reduced to the following:

A. Deploy

B. Remove/replace

C. Cargo transfer (includes film retrieval, refurbishment, loading, and special handling)

D. Inspect

E. Maintain (includes alignment, cleaning, focusing, sensor update)

F. Assemble (includes installation, attachment)

G. Repair

H. Operate and monitor

I. Data acquisition (includes measurement, photography)

J. Satellite recovery

K. Astronaut escape/rescue

L. Astronaut translation

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT

MISSION EXPERIMENT	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue
OPERATIONAL & PLANNED																						
Gemini IV										X						X				X		
Gemini IX A	X							X								X	X			X		
Gemini X	X				X			X							X	X				X		
Gemini XI															X	X	X			X		
Gemini XII	X		X	X	X			X	X	X					X	X	X			X		
Apollo 9																						
ATM	X	X	X		X			X		X					X							
EOSS	X		X	X	X	X		X	X	X			X		X	X	X		X	X	X	X
ADVANCED MISSIONS																						
• Astronomy																						
Solar spectrometer	X	X	X	X	X	X	X	X	X													
*1 m nondiff. telescope		X		X	X		X	X	X													
*ATM/80 cm solar telescope		X	X	X	X		X	X	X													
*1 m telescope		X	X	X	X		X		X													
Sky survey	X	X	X	X	X	X	X	X	X													
mm radio astr.	X		X	X		X	X	X	X													
*Long wave radio astr.	X		X	X		X	X	X	X													
*X-ray focusing telescope	X	X	X	X	X		X	X	X		X	X										
*EMR payload	X	X		X	X		X	X	X	X			X									
Stellar/Gal. X-ray spec.	X		X	X	X		X	X	X													

*Advanced NASA experiment

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT (Cont.)

MISSION EXPERIMENT	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue
X-ray sky survey	X		X	X	X		X	X	X													
• Bioscience																						
Soft capture-microorg.	X				X			X						X								
Bacterial spores	X				X	X		X							X							
Cross breeding					X	X		X														
Rodent colony					X	X		X	X													
Protozoans					X					X						X						
Multitropic - plants		X			X	X										X						
Bio package	X			X	X			X					X		X	X						
*Primate biomed.	X			X	X	X		X	X	X						X						
Physiol. Resp.-mannals	X				X			X					X									
Musculoskel. resp.	X				X	X		X								X						
Urine-fecal anal.	X				X	X		X									X					
• Physical Science																						
Optical surf. erosion				X				X														
*Artificial Aurora	X		X							X							X					
Meteoroid collection	X				X			X									X					
Micromet. distribution	X				X			X	X							X	X					
Micromet. analysis	X				X			X								X						
Mass equivalence										X							X					

*Approved NASA experiment

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT (Cont.)

MISSION EXPERIMENT	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue
Grav. grad. meas.	X																					
Liquid drop dynamics	X	X								X							X					
Vapor condensation	X									X							X					
Atomic & molecular	X		X							X												
Ionizing radiation	X		X													X	X					
Cosmic ray protons			X			X				X						X	X					
Mag. field lines			X													X	X					
*Spacecraft environment		X				X							X			X	X					
Sat. inspection				X																		
Dosimeters	X												X									
Heat pipe	X			X	X								X			X						
Radiation shield					X											X				X		
• Earth Sciences																						
Mapping-forest-crustal studies		X	X	X	X			X					X			X		X				
Mineral deposits		X	X	X	X			X					X			X		X				
Synoptic earth map - Global field map		X	X	X	X			X					X			X		X				
Ocean coastal survey - floor topography		X	X	X	X			X					X			X		X				
Geologic synoptic survey		X	X		X			X					X			X						
• Meteorology																						
Horiz. wind velocity measurements		X	X	X	X			X		X			X					X				

*Approved NASA experiment

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT (Cont.)

MISSION EXPERIMENT	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue	
Ionosphere recombin. rates		X	X	X	X			X								X							
Refraction star track			X					X					X										
Pollution analysis		X			X																		
Synoptic mapping		X			X																		
● Comm - NAV																							
*Long boom interferometer					X								X				X						
Mother-daughter sat. interferometer	X			X									X										
RF reflecting structure	X			X									X							X			
Noise-interference survey	X							X									X			X			
Space structure assembly			X		X					X						X	X			X			
Large antenna align & calibration			X														X			X			
Grav. grad. stabilized lenticular structure	X																			X			
60 ft. paraboloid antenna			X	X	X			X					X			X	X			X			
Large antenna - deploy and erection	X			X						X			X										
*Advanced tech. antenna			X	X	X			X					X										
Echo sat. observation													X							X			
TV broadcast sat.	X		X	X	X		X						X							X			
Global com. satellite	X		X	X									X			X				X			
TV satellite	X			X				X					X				X			X			
Atmosph. scintillation			X		X												X						

*Approved NASA experiment

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT (Cont.)

MISSION EXPERIMENT	FUNCTIONS																						
	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue	
Optical sys. adjust-align			X																				
Eval. of radar compon.				X									X										
Laser comm.			X					X															
• Advanced Technology																							
SIVB lab solar cell array	X		X	X				X					X						X	X			
Radioisotope transfer				X	X			X								X				X			
Evaporation-condensation					X			X								X			X	X			
Storable extendable rod structure	X			X									X						X				
*Large structure deploy.	X		X	X									X						X				
High capacity heat pipe				X									X			X				X			
Nuc. & solar rad. shielding																X				X			
Fluid trans. techniques			X	X									X										
Long term cryo storage				X																X			
Refurbish ablative material					X				X											X			
Space radiator repair				X					X											X			
Solar panel repair				X	X			X											X				
RCS repair				X				X															
• Orbital Operations																							
large sturc. deployment	X			X															X	X			
Personnel retrieval-rescue					X															X			

*Approved NASA experiment

TABLE 2-1 EVA FUNCTIONS - MISSION/EXPERIMENT (Cont.)

MISSION EXPERIMENT	Deploy	Film Retrieval	Align	Inspect	Cargo Transfer	Refurbish	Update Sensors	Remove & Replace	Repair	Operate	Verify	Focus	Monitor	Special Handling	Load	Install	Assemble	Clean	Measure	Photograph	Satellite Recovery	Rescue
Grav. grad. stab. struc.	X			X									X							X		
Data capsule delivery system				X	X										X							
Cargo transfer				X	X												X					
*EOSS	X		X	X				X	X	X										X		
Fluid transfer				X									X				X					
Sat. ops & inspection				X															X	X		
Sat. capture				X	X			X											X	X		
Repair heat shield				X					X											X		
Dock mechanism repair				X					X											X		
● Biomed. - Behavior																						
EVA metabolic costs																X						
Higher mental processes																						
Vis. acuity																			X			
Auditory sensitivity																			X			
Gross movements																			X			
Integrated perf. eval.	X				X					X									X			

*Approved NASA experiment

2.5 REQUIREMENTS ANALYSIS

The specific requirements associated with each EV function will depend upon the mission. The general types of requirements to be identified are information and performance requirements. Information requirements consist of the information needed to perform function and presentation parameters such as data rates, duration of presentation (continuous or on demand), accuracy requirements (error tolerances), etc. Performance requirements consist of the activities which make up the function as well as constraints on performance such as time to respond, time to perform, energy expenditures required, and accuracy requirements.

For each of the EVA functions listed above, general information and performance requirements are given in Table 2-2. The EV system which best satisfies the requirements of a specific mission should be selected for use in that mission.

TABLE 2-2

REQUIREMENTS ANALYSIS FOR EV FUNCTIONS

EV FUNCTION	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS
A. Deploy	Deployment schedules Knowledge of procedures Feedback of deployment initiation Monitoring information Existence of contingency conditions Malfunction detection information Fault isolation information Verification of completion Decision information	Time, accuracy, decision, and energy requirements for: deploy initiation control of deployment malfunction isolation corrective action deployment termination deployment verification
B. Remove/ Replace	Schedules Location of package to be removed Unlock procedures Removal decision information Identification of replacement package Installation procedures Locking procedures Feedback-adequacy of replacement Replacement decision information Malfunction detection/ isolation information	Time, accuracy, decision, and energy requirements for: locating expended package unlocking removing storing acquiring replacement aligning install locking verifying
C. Cargo Transfer	Schedules Identification of cargo to be transferred Destination of cargo Route of transfer Potential obstructions/ hazards enroute Monitoring information -transfer direction control -transfer rate control	Time, accuracy, decision, and energy requirements for: cargo acquisition-unstow cargo loading control of transfer: -initiation -direction -rate -obstacle avoidance -termination

TABLE 2-2 (Continued)

EV FUNCTION	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS
C. Cargo Transfer (Continued)	Arrival at destination Verification of transfer Decision information Malfunction detection/ isolation information	Alignment at destination Unloading
D. Inspect	Schedules and checklists Visual observation Inspection standards Tactual test information Identification of con- tingencies Decision information	Time, accuracy, decision, and energy requirements for: verifying structural integrity verifying connections verifying equip. operation verifying alignments identifying need to maintain identifying needs to repair identifying needs to replace identifying needs to remove identifying needs to abort
E. Maintain	Schedules for periodic maintenance Periodic maintenance pro- cedures Decision information Identification of tools and test sets Verification of completion Checkout information Maintenance standards	Time, accuracy, decision, and energy requirements for activation, performance, and termination of: servicing cleaning filling focusing aligning calibrating checkout tightening
F. Assemble	Assembly schedules Assembly procedures Decision information Identification of tools and aids Verification of completion Identification of con- tingencies	Time, accuracy, decision, and energy requirements for activation, performance, and termination of: connecting-attaching installing cutting mating of subassemblies

TABLE 2-2 (Continued)

EV FUNCTION	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS
F. Assemble (Continued)	Assembly standards Checkout information	subassembly handling erection assembly test and checkout
G. Repair	Schedules Identification of component to be repaired Repair procedures Identification of tools Verification of completion Repair standards Decision information	Time, accuracy, decision, and energy requirements for activation, performance, and termination of: ident. of repair replacement patching component replacement structures repair electrical repair mechanical repair line-valve repair verification of repair
H. Operate and Monitor	Schedules Sequence of operations Monitoring information Contingency information Decision information	Time, accuracy, decision, and energy requirements for: operation activation conduct of operations monitoring of operations interruption of operations malfunction isolation verification of operations termination of operations
I. Data Acquisition	Schedules Identification of data to be acquired Knowledge of constraints Acquisition procedures Verification of completion Verification of data validity Data acquisition standards Decision information	Time, accuracy, decision, and energy requirements for activation, performance, and termination of: sensor activation data recording photography measurements

TABLE 2-2 (Continued)

EV FUNCTION	INFORMATION REQUIREMENTS	PERFORMANCE REQUIREMENTS
J. Satellite Recovery	Satellite location Recovery modes and procedures Stabilization procedures Verification of completion Decision information Contingency information	Time, accuracy, decision, and energy requirements for: satellite location rendezvous final approach inspection stabilization capture secure verification
K. Astronaut Escape/Rescue	Astronaut location Time constraints Nature of contingency Route to astronaut away from hazard Decision information Modes and procedures	Time, accuracy, decision, and energy requirements for: astronaut rescue -approach -stabilization -acquisition -secure -return astronaut escape -egress area -translate -ingress safe area
L. Astronaut Translation	Translation schedule Routes and worksite location Procedures Decision information Life Support information Translation system status	Time, accuracy, decision, and energy requirements for: -egress -checkout translation systems -route selection -direction control -direction change -obstacle avoidance -system monitoring -rate control -stabilization -arrival at worksite -termination of translation

SECTION III

FREE SPACE ACTIVITY SYSTEMS

3.0 FREE SPACE ACTIVITY SYSTEMS

Future missions will require that certain functions be performed in free space; therefore, a means of accomplishing these functions must be developed. In order to avoid confusion associated with the designator "extravehicular" which may be construed as extravehicular activity (a term usually associated with man external to the vehicle), the general class of means to perform functions will be termed Free Space Activity Systems (FSAS) (The FSAS derives its name from the fact that it is a system which will perform activities in free space). The activities to be performed include those identified in Section 2.0. In this section, the subsystems of the FSAS will be discussed, and a classification scheme for categorizing alternate FSAS concepts will be described.

3.1 FSAS SUBSYSTEMS

In an excellent, comprehensive survey of remote manipulator or teleoperator requirements and state-of-the-art equipment, Johnson and Corliss (1967) identified ten (10) subsystems for a teleoperator. These include:

- Actuator Subsystem - the effector portion of the teleoperator
- Sensor Subsystem - acquires and transmits data concerning the environment
- Control Subsystem - decision making and command functions
- Communications Subsystem - including command links and data links
- Computer Subsystem - information processing
- Propulsion Subsystem
- Power Subsystem - electric, hydraulic, mechanical, nuclear, or other power

- Attitude Control Subsystem - for stabilization
- Environment Control Subsystem
- Structural Subsystem

While this list is inclusive in terms of teleoperator functions and required subsystems, the list can be abbreviated for purposes of this report. The FSAS is primarily concerned with the roles, responsibilities, and requirements of the man. Therefore, the sensor and communications subsystem can be combined with the control subsystems (since one class of FSAS will be manual EVA), designate the attitude control subsystem as the stabilization subsystem, and add support subsystems (such as lighting) which aid in the performance of a function. The list of subfunctions for the FSAS then becomes:

- Translation Subsystem
- Stabilization Subsystem
- Control Subsystem
- Actuator Subsystem
- Environment Control Subsystem
- Support Subsystems

3.1.1 Translation Subsystem

The prime objective of an FSAS will be to perform one or more of the functions identified in Section 2.0. In order to accomplish a given function, the FSAS must be capable of being translated or at least of translating the actuator subsystem to the location (worksite) where the function is to be performed. For some functions, not only must the actuator be translated, but cargo, tools, incapacitated astronaut, support equipment, structures, and satellites must also be moved by the FSAS.

3.1.2 Stabilization Subsystem

This subsystem includes the means of maintaining attitude to a reference, determining required changes in attitude, and effecting those changes. For different classes of FSAS design approaches, subsystem equipment can range from astronaut restraints to reaction control systems. Stabilization will be required during FSAS translation and during actuator operation.

3.1.3 Control Subsystem

The control subsystem includes the means for determining control requirements and for effecting the control. This subsystem exercises an executive function over all other subsystems such that the control of the operations performed by those subsystems is directed by it. Specific control functions include:

- Control of translation direction
- Control of rate of translation
- Control of stabilization while translating
- Control of stabilization at the worksite
- Control of actuator operations
- Control of life support subsystem
- Control of support subsystems

3.1.4 Actuator Subsystem

The actuator includes the tools, grapplers, etc., used to perform the functions described in Section 2.0. The location of actuator subsystem operation defines a worksite when the actuator is not translating. In EVA the astronaut's gloved-hand or a tool held by the hand could comprise the actuator subsystem of that class of FSAS. In a remote subsystem, a pincher attached to a remote manipulator is an example of an actuator subsystem.

3.1.5 Environment Control Subsystem

The environment control subsystem (ECS) includes all means of protecting the astronaut from extremes of temperature, radiation, and meteorite bombardment while providing him with oxygen, carbon dioxide removal, and thermal balance.

3.1.6 Support Subsystem

Support subsystems include the ancillary equipment, such as lighting and safety devices (tethers), needed for the completion of a function.

3.2 FSAS CLASSES

It is assumed that an FSAS will be employed only on manned missions and that man will be involved to some extent in all system classes. In developing the classifications scheme, the same guidelines were used as those in the classification of functions, i.e.:

- the scheme must be all inclusive and must be capable of handling all candidate FSAS design approaches;
- the scheme must ensure differentiation or discrimination among classes such that any given candidate FSAS is easily assigned to one and only one class; and
- each class must be internally consistent such that whatever is said of the total class applies to each system assigned to the class.

The purpose for classifying FSAS candidates is to reduce the number of feasible system approaches to a manageable size. This approach facilitates the task of describing the systems at the cost of specificity, since what is said of a class must apply to all members of the class.

The initial segmentation of FSAS alternate concepts includes a taxonomy of those classes which require EVA as opposed to those which require only IVA. In EVA the man (plus a remote manipulator) is located in free space, external to the prime vehicle, with no other life support but his suit and associated umbilical or portable expendible containers. In IVA the man (using a remote manipulator) is located in a pressurized environment where he needs no suit. This environment could be located in the prime vehicle or within a satellite vehicle.

Figure 3-1 depicts the two major classifications, i.e., Manned-EVA and Manned-IVA, along with their appropriate subclasses. The essential characteristics, astronaut locations, and representative examples for each class and subclass are presented in Table 3-1.

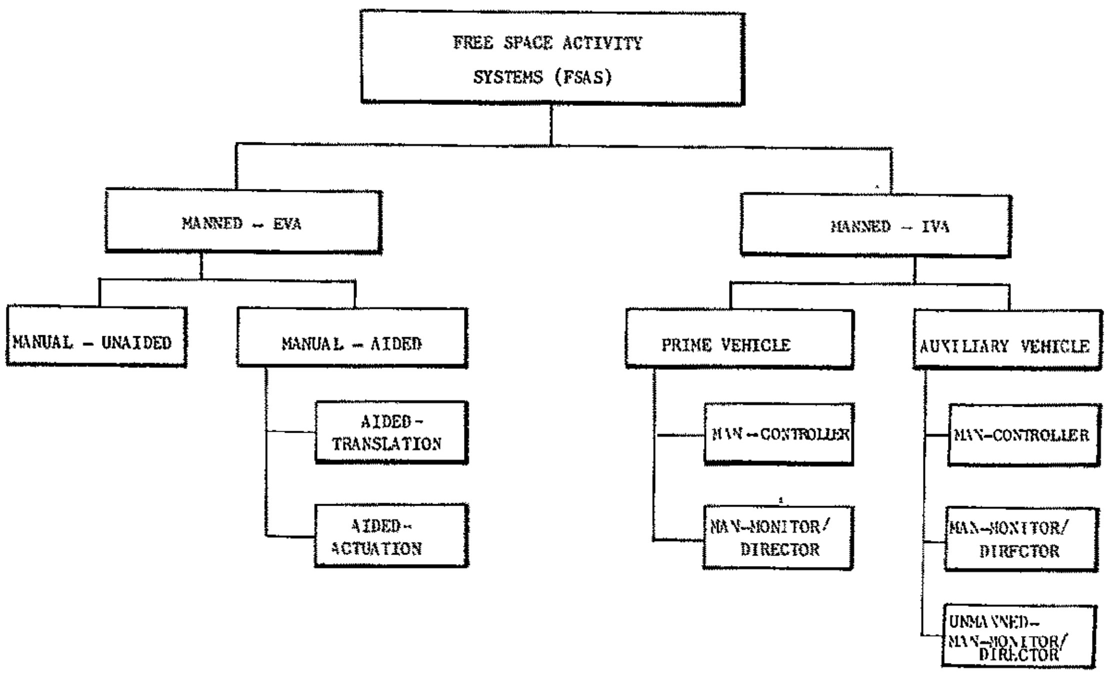

FIGURE 3-1. FSAS CLASSIFICATION SCHEME

TABLE 3-1 DESCRIPTION OF FSAS CLASSES

CLASS/ SUBCLASS	ASTRONAUT LOCATION	SUBSYSTEMS/DISTINGUISHING CHARACTERISTICS						EXEMPLIFYING SYSTEMS
		TRANSLATION	STABILIZATION	CONTROL	ACTUATION	ECS	SUPPORT	
Manned EVA								
• Unaided	EVA	Handrails tethers	Restraints handholds	Muscular controls	Hand-tools	Suit ELSS-PLSS	Lighting guards	AAP-ATM, Gemini
• Aided -translation	EVA	Powered mechanical propulsion	Translation powered actuation re-straints	Translation -man control -programmed	Hand-tools	Suit ELSS-PLSS	Lighting power propulsion	AMU, Serpentuator, Bendix Work Platform
-Actuation	EVA	Handrails tethers	Actuation structural	Actuation man control	Force amplifi-cation remote manipu-lator power tools	Suit ELSS-PLSS	Lighting sensors	Bendix Work Platform
Manned IVA								
• Prime Vehicle -man control-ler	IVA prime vehicle	Structural linkage	Structural linkage	Remote	Remote	Prime vehicle	Lighting video	Remote manipulator-man controlled
-Man monitor director	IVA prime vehicle	Structural linkage	Structural linkage	Programmed	Remote	Prime vehicle	Feedback logic	Programmed Serpentuator
• Auxiliary vehicle-man controller	IVA-prime or satellite vehicle	Reaction jet propulsion	Attitude control	Flight control	Remote	Aux. vehicle	Lighting video	LTV Space Taxi
-Man monitor director	IVA-prime or satellite vehicle	Reation jet propulsion	Attitude control	Programmed	Remote	Aux. vehicle	Lighting video	Automatic Remote Man Manipulator System
-Unmanned man, monitor/ Dir-ector	IVA-prime vehicle	Reaction jet propulsion	Attitude control	Flight control	Remote		Lighting video	G.E. Remote Manipulator Spacecraft

SECTION IV

MANUAL EXTRAVEHICULAR ACTIVITY

4.0 MANUAL EVA

4.1 INTRODUCTION

The NASA definition for EVA refers to any operation conducted by an astronaut while in a pressurized suit in a vacuum environment. While this environment could include the interior of a pressurized vehicle (e.g., the orbital workshop), the EVA to be discussed in this report applies only to activities conducted in free space external to a vehicle during orbital missions.

The free space environment is a near-perfect vacuum and has wide temperature extremes (varying from -200° to +160°) high-intensity and high-contrast light conditions, micrometeorites, galactic and solar radiation, and virtually no gravity. However, the Astronaut's environment is not totally that of free space. Aside from loss of gravity, all other environmental conditions are controlled or modified by the Astronaut's spacesuit and associated life support system. The suit provides a livable atmosphere (i.e., breathable, under sufficient pressure) and protection from extremes in temperature, illumination, radiation, and micrometeorites.

While the spacesuit provides for the Astronaut's physical well-being, it also limits his performance capabilities. The bulkiness of the spacesuit reduces the Astronaut's mobility, the forces he can apply, and his "sense of touch" external to the suit. His performance capabilities are further degraded by the weightlessness of orbital EVA. Weightlessness interferes with his ability to judge the orientation of his whole body. This change from the gravity environment requires that Astronauts develop new skills in moving themselves and other objects from point to point. Objects in free space will have the property of "mass" but not the property of "weight." Therefore, if an Astronaut releases an untethered tool, recovery might be impossible; if he translates too fast, stopping might be difficult and dangerous.

This section will describe the technology required to support astronaut EVA as a means of accomplishing the functions described in Section 2.0. Space suits and life support systems will be discussed, and equipment requirements for worksite and translation activities will be identified. When available, requirements for additional research and development of EVA equipment will be identified.

4.2 SPACE SUITS

As described by Bell (1969), pressure suit assemblies have been used to fulfill three basic functions: 1) serve as a backup pressure vessel to the spacecraft cabin, 2) serve as a protective cover in case of fire or toxic environmental conditions, and 3) serve as the primary pressure vessel for EVA. Although it provides a protective, comfortable environment for the EVA astronaut, the suit is also the major constraint on his ability to perform mission functions. The suit helmet limits the field of vision, and the suit itself limits body/limb mobility and hand/finger dexterity. During Gemini missions it was observed that fatigue was significant whenever a suit position different from the neutral position was held for some time. Due to suit mobility limitations, the Gemini EVA astronaut could not perform sustained work below the waist level or above shoulder level. In the development of early spacesuits, functional mobility had been a secondary consideration; primary emphasis was on pressure and thermal protection. These suits were logical successors to early aircraft protective garments (North American Rockwell, 1968).

The development of spacesuits can be described in terms of operational suits and advanced suits. Operational suits include those used in Gemini and Apollo EVA. Advanced suits include the Litton RX-5 and Ames AX-2 hard suits, the space activity suit, and the advanced extravehicular suit.

4.2.1 <u>Gemini Suits (From Summary of Gemini EVA-NASA-MSC-G-R-67-2, 1967)</u>

The Gemini suit was initially designed for IV use and was successfully modified for EVA. The suit consisted of a multi-layer fabric system comprised of a comfort liner, gas bladder, structural restraint, and outer protective layer. A gas distribution system inside the suit directed oxygen flow to the helmet area for metabolic use and to all areas for thermal control. For EVA use, the following equipment was added to the basic suit:

- EV cover layer to provide thermal and micrometeoroid protection
- EV gloves to reduce conductive heat transfer
- Low emittance coating on exterior surface of pressure visor to minimize radiant heat loss
- Sun visor to attenuate solar illumination

The basic Gemini EVA suit was the G-IVC suit with modifications. For the Gemini IV mission, the suit EV cover layer consisted of an outer protective layer of high-temperature resistant nylon, a layer of nylon felt for micrometeorite protection, several layers of aluminized mylar and unwoven dacron, and two additional layers of high-temperature nylon. The G-IVC helmet was equipped with a detachable EV visor consisting of two over visors. The outer or sun visor was gray-tinted plexiglass coated with thin gold film to reduce transmission of visible light to 12 percent. The gold film also absorbed UV and reflected solar IR energy. The second visor was designed to inhibit transmission of UV and to provide impact protection for the outer visor. The G-IVC gloves were designed to provide thermal protection against surface temperatures ranging from 250° to -150° for two minutes.

In the Gemini VIII suit, the micrometeoroid protective layers of the Gemini IV spacesuit were replaced with two layers of neoprene-coated nylon. Integrated pressure thermal gloves were also added to replace the overgloves used in Gemini IV.

The Gemini IXA suit added a stainless steel fabric to the leg covers to protect against impingement of AMU thrusters. The plexiglass visor was replaced with a polycarbonate visor, and the impact was eliminated. For Gemini X, red lenses were added to the fingertip lights to avoid damage to film, and visor anti-fog kits were used. The Gemini XI and XII suits were basically the same as Gemini X.

The primary problems encountered during Gemini EVA were due to limitations in the mobility of the space suits. Since the suits had been designed primarily for IVA, the neutral position was a sitting position. The suit arms were positioned to enable easy access to Gemini flight controls. Whenever a crew member moved within the suit, he had to overcome the forces which tended to return the suit to its neutral position. These forces were significant when the arms were raised above shoulder level. Due to restricted arm mobility, an EVA pilot moving along a handrail had to move his hands in front of him with a side-to-side motion rather than hand-over-hand. Glove mobility was satisfactory for brief periods of time; however, long term activity tired the pilot's hands. The bulk of the cover layer restricted pilot mobility as did the increase in suit pressure from 3.7 to 4.2 PSIA.

4.2.2 Apollo Suits

Operational suits used for Apollo missions include the A-6L and the A-7L. The A-7L represents the spacesuit assembly for the Apollo lunar missions. When configured for orbital or lunar surface EVA, the A-7L is defined as the Extravehicular Mobility Unit (EMU). EMU systems include a Pressure Garment Assembly (PGA) which is integrated with the A-6L Thermal Meteoroid Garment to form the Integrated Thermal Meteoroid Garment (ITMG), the EV Visor Assembly, the Liquid Cooled Garment, the Portable Life Support System, and the Emergency Oxygen Purge System (OPS). The PGA, an anthropomorphic ensemble, affords protection to the astronaut from the space environment by maintaining suitable atmosphere and pressure, thermal control, communications, and protection from radiation and meteoroid encounters. For pressurization oxygen is supplied from external sources at 3.7 $\pm$ .2 PSIA. PGA subsystems consist of the Torso Limb Suit with ITMG, helmet and visor assembly, glove assemblies (IV and EVA), controls and displays, and lunar overshoes.

Torso Limb Suit with ITMG

The Torso Limb Suit and ITMG of the A-7L weighs 47.27 pounds. Astronaut body mobility in this suit has been documented in the International Latex Corporation CEI Detail Specification 2001A (August, 1967). Data from this document are presented in Table 4-1. The Torso Limb Suit assembly includes an inner liner, ventilation distribution system, primary pressure bladder, and outer covering.

TABLE 4-1 EVA ASTRONAUT SUIT MOBILITY (A-7L WITH ITMG)

MOVEMENTS	RANGE OF MOVEMENT (Degrees)
A. Neck Mobility	
Flexion (forward - backward)	120
Flexion (left-right)	30
Rotation (left-right)	140
B. Shoulder Mobility	
Adduction	35
Abduction	125
Lateral - Medial	145
Flexion (arm up/down)	170
Extension (arm down/back)	47
Rotation - Down up (X-Z Plane)	
Rotation (X-Z Plane)	
Lateral Rotation	35
Medial Rotation	95
C. Elbow Mobility	
Flexion - Extension	137
D. Forearm Mobility	
Supination (palms up)	90
Pronation (palms down)	75
E. Wrist Mobility	
Extension (forward)	56
Flexion (backward)	57
Flexion (abduction)	42
Flexion (abduction)	30
F. Trunk	
Trunk Rotation (left -right)	5
Torso Flexion (left - right)	5
Torso Flexion (forward)	95
Torso Flexion (backward)	5
G. Hip Mobility	
Abduction (leg straight)	45
Abduction (hip bent)	30
Abduction (hip bend)	35
Rotation Lateral (sitting)	30
Rotation Medial (sitting)	30
Flexion	115
Extension	20
H. Knee Mobility	
Flexion (standing)	110
Rotation (medial)	15
Rotation (lateral)	15
Flexion (kneeling)	140
I. Ankle Mobility	
Extension	40
Flexion	35
Abduction	25
Abduction	25

Helmet/Visor Assembly

The PGA helmet is constructed of clear lexan in a bubble shape. The astronaut's head is free to move within the confines of the helmet, but his vision is limited by the location of the torso neckring and by mobility restrictions which limit rotation and elevation of his head. The A-6L helmet is 24.6 cm in width and 31.3 cm in depth. The visual fields with the A-6L are 90° upward, 105° downward, and 120° laterally, left and right. The critical visual envelope for the A-7L includes the following:

- Temporal - 90°
- Superior temporal - 62°
- Superior - 80°
- Inferior temporal - 85°
- Inferior - 70°

The visor assembly consists of the pressure (inner) visor, the impact (middle) visor, and the sun (outer) or gold visor. The transmittance of the total visor assembly is 10 percent in the visible range (.39 to .75 microns) and one percent in the UV range (.25 to .39 microns). The total transmittance in the IR range is 5 percent (.75 to 2.5 microns). The helmet and EV visor assembly of the A-7L weighs 3.10 pounds.

EV Glove Assembly

The EV glove assembly consists of a thermal protective device which interfaces with the suit prior to EVA. The assembly covers the entire hand and has an internal cuff which extends the protective covering well above the wrist disconnect. The EV glove is a modified glove called the TMG Pressure Glove Assembly onto which a thermal insulating cover is secured. The EV glove shell assembly is multi-layered and similar in construction to the ITMG. In the palm and inner finger area, a woven metal (chromel-R) fabric provides resistance to abrasion and fire. The metal fabric is coated with a silicone dispersion compound to improve anti-slip characteristics. The outer cover is conformal and does not appreciably restrict the dexterity of the inner ITMG pressure glove assembly

The A-7L EV glove is designed to maintain hand temperature within a range of 60° to 103°F and weighs 2.8 pounds. Orbital EVA specifications for the EMU glove demand the capability to grasp a 1-inch diameter rod (temperatures ranging from 250° to -150°F) with medium firm grip for 90 seconds. Cable restraints are incorporated into the glove design to limit extension during pressurization. The capabilities of the A-6L gloved hand are presented in Table 4-2.

Controls and Displays

EMU controls include the ventilation diverter valve, pressure relief device, and purge device. A pressure gage serves as the primary display.

Auxiliary Equipment

Auxiliary EMU equipment includes the following:

- Scissors - in right lower leg, out-board
- Pen lights - upper left arm
- Pencil/pen - upper left arm
- Data book - left lower leg
- Checklists - right lower leg
- Sunglasses - upper right arm
- Dosimeter - inside right thigh

4.2.3 Advanced Suit Concepts

As classified in the North American Rockwell Extravehicular Engineering Activity Report (1968), suits developed in the 1970-80 time frame will fall into two groups--soft suits and hard suits. Soft suits include improved Apollo suits, mechanical pressure or space activity suits, two pressure suits, advanced EV suits, and liquid filled suits. Hard suit concepts include the Litton RX-5, the Ames AX-2, servo powered hard suits, and non-anthropomorphic hard suits.

TABLE 4-2

ASTRONAUT HAND MOBILITY IN THE A-6L SUIT

Dexterity - expressed in terms of percent of nude hand capability

Pick up $\frac{1}{4}$ inch pins -	right-hand	33%
	left-hand	19%
	both hands	12%
Pick up $\frac{1}{2}$ inch pins -	right-hand	65%
	left-hand	59%
	both hands	42%

Torquing Capability

	Object Size-inches dia.	Force in Inch lbs.
Fingertip	.75	3.8
	1.00	5.2
	1.25	7.6
	1.50	9.6
Finger curl around	.75	3.8
	1.00	5.2
	1.25	7.6
	1.50	11.4
Screwdriver	4.25 in. long 1.00 in. dia.	
pronation		51.66
supination		48.66
Ball	2 in. dia.	
pronation		56.66
supination		60.83
Knob		
pronation		105.50
supination		105.83

Activation Time - percent of nude hand capability

Knobs	70%
Pushbutton	40%
Toggles	60%

Modified A-7L (A-7L-B)

The A-7L-B suit, designed for Apollo 16 and Apollo Applications Program missions, provides increased waist joint mobility and improved arm and shoulder mobility. The A-7L-B with ITMG will weigh 60.92 pounds as compared with the 61.1 pound weight of the current A-7L.

Advanced Extravehicular Suit (AES)

The AES assemblies utilize near constant volume joint systems for maximum mobility at the shoulder, elbow, waist, hip, knee, and ankle joints with minimum energy expenditure. Target weight is 68.16 pounds, with ITMG. The suit is presently in the prequalification stage of development by AiResearch and Litton and should be available for support of Apollo 17 (August, 1971).

Mechanical Pressure Suit

In the mechanically pressurized suit, respiratory counter-pressure is supplied to the skin by mechanical means rather than by gas pressure. One concept for the mechanical suit, the space acitivity suit (SAS), utilizes a strong elastic cloth material in the shape of a tight fitting, leotard-type garment to apply mechanical counter-pressure against the body. A partial pressure helmet and full breathing bladders are part of the assembly. Thermo regulation is achieved by simple evaporation of sweat through the porous net construction. In EVA a light-weight outer garment would be required for micrometeorite and thermal radiation protection. This concept provides improved mobility, flexibility, and dexterity at small metabolic costs, simplicity in design approach, low risk of suit damage, and easy and natural thermo-regulation without additional power or cooling mechanisms. However, the concept presents problems in difficult donning, likelihood of materials degradation over prolonged exposure to the space environment, and lack of smooth application of adequate elastic counter-pressure to all parts of the body.

Two Pressure Suits

A soft suit concept has been advanced which would limit the pressure around joints to provide proportional reduction in the force required to move a limb. A sealing mechanism would be required between regions of different pressure. According to the NAR EVA report, this concept is not feasible because of problems in sealing off areas without restricting blood flow and difficulties in differential pressures for cardiovascular system functioning.

Liquid Filled Suits

In this concept the astronaut is immersed to the neck in a pressurized liquid medium, and a breathable atmosphere is supplied to the helmet. The liquid transfers heat and liquid wastes from the suit, provides radiation protection, and balances the atmospheric pressure of the lungs. Difficulties arise in sealing off the liquid from the helmet without cutting off blood flow to the head. A fluid would be required which would not cause skin irritation.

The Litton RX-5 Hard Suit

The RX-5 utilizes near-constant volume joint systems for shoulder, elbow, waist, hip, knee, and ankle mobility. The basic structure is a composite layer of thin aluminum sheet faced with fiberglass honeycomb and covered by a layer of fiberglass sheet. Since future spacecraft environments will consist of two gases pressurized at 7 PSIA, an advantage of the design is that it allows pressurization of up to 7 PSIA without mobility degradations. The total weight of the RX-5 including integrated thermal and micrometeoroid protection is approximately 67 pounds. Portable life support system components may be incorporated to make a totally integral suit/life support system. Problems with the suit include bulky storage and greater weight than soft suits.

Ames AX-2 Hard Suit

The Ames AX-2 was developed using a rigid structure similar to the RX type hard suit. In the Ames concept, however, a series of rotary bearings arranged in a "store pipe" fashion are utilized for the prime shoulder, elbow, hip, knee, and ankle mobility joint systems. In combination with the rotary bearings in the hip and knee areas, a series of metal bellows is used for joint mobility.

Servo-Powered Hard Suits

Servo-powered suits have been proposed to provide the astronaut with hundreds of pounds of force. Power supply actuators, sensors, and mechanical linkage would be mounted on the exterior of the suit within an exoskeletal framework.

The projected technological requirements for suits were developed by North American Rockwell (1968). These requirements are summarized in Table 4.3.

4.3 LIFE SUPPORT SYSTEMS

In addition to the spacesuit, the life support system controls the environment of the EVA astronaut. This system supplies to the suit a breathable atmosphere, provides for the removal of carbon dioxide, and provides cooling for the body. For Gemini and Apollo missions to date, the breathable atmosphere has consisted of oxygen. During Gemini missions, the cooling was accomplished by gas flow through the suit while Apollo used a liquid cooled garment consisting of a network of tubes through which water is circulated.

During Gemini missions the primary constraint on EVA was the Life Support System (LSS). On some missions exceeded LSS limits led to the early termination of the EVA. The LSS for Gemini IV, the first operational EVA, consisted of a chest pack to control suit pressure and oxygen flow (the ventilation control module) and a 25-foot umbilical which supplied oxygen to the VCM and to the suit from the spacecraft. At the conclusion of the EVA, the astronaut expended a very high effort pulling the hatch fully closed. During this acitivity he became greatly overheated, and the cooling capability of the VCM was exceeded. The astronaut perspired heavily and experienced light visor fogging. It was concluded that the VCM was adequate for nominal EVA but the cooling capabilities with 8.2 lb/hr flow were insufficient for the high work levels expected in emergency conditions.

Gemini IXA, X, XI, and XII utilized an uprated chest pack--the Extravehicular Life Support System (ELSS). Oxygen was supplied to the ELSS via an umbilical and delivered to the suit at a flow rate of either 5.1 or 7.8 lbs/hr as selected by the astronaut. The ELSS chest pack performed

TABLE 4-3 SPACE SUIT TECHNOLOGY REQUIREMENTS

SUBSYSTEM	REQUIREMENT	STATE-OF-THE-ART	CURRENT WORK	NEEDED WORK
Pressure Containment	3.5 ± .2 PSIA	Bladder - fabric layer	- hard shell - shell-soft limbs - mechanical pressure elastic suit	- reduce weight - reduce volume - equalize counter-pressure
Limb-Joint Mobility	Same as unsuited	- constant volume bellows - rotating ring	- elastic bellows with cables - metal/fabric convolute - rotating segment	- reduce friction - elastics - equalize counter-pressure
Glove Mobility	Dexterity/tactility of nude hand	- molded bladder with fabric and mechanical restraints	- low pressure reduction - mechanical pressure glove	- improved palm restraint - materials
Helmet	Unlimited visibility and protection	- molded clear polycarbonate visors	- none	- improved visual envelope - helmet/torso seal
Bio-instrumentation	Monitor	- EKG	- increased monitoring	- flight instrumentation
Waste Management	Collect wastes	- urine collection (1500 cc) - fecas collected and stored in suits	- none	- psychological acceptability - hygienically improved

satisfactorily during EVA in Gemini X and Gemini XII. However, during EVA of both Gemini IXA and XI, pilots experienced fatigue and high energy expenditure in maintaining body position. The high workload led to visor fogging and heavy perspiration. The heat exchanges and moisture control of ELSS were designed for a nominal metabolic rate of 1400 BTU/hr for 86 minutes and a maximum rate of 2000 BTU/hr for 10 minutes. Ground tests indicated that satisfactory cooling and moisture control could be maintained when work levels and metabolic rates were less than 2000 BTU/hr. However, heart rate data and post-flight simulation of the activities indicated that this limit was exceeded. At high work levels the gaseous flow used for cooling was incapable of evaporating all the moisture produced from heavy perspiration. The extreme fatigue was assumed to be due to inadequate removal of high concentrations of carbon dioxide.

The results of the Gemini missions show the criticality of sizing life support systems for the range of workloads expected (either nominal or contingency) and the importance of preflight simulation fidelity. A rate of 2000 BTU/hr is associated with such Earth-bound activities as level skiing at 3 mph, carrying a 67-pound load while walking at 4.1 mph, and cycling at 10 mph (Webb, 1964). Such activities, while representative of moderately heavy workloads, are not overly strenuous. While there is admittedly a great deal of variability among individuals in metabolic rate due to temperature, body size, and diet, the figures reported above indicate that the use of 2000 BTU/hr as a maximum rate in sizing the ELSS was unrealistic.

In Apollo missions, the limitations of the gaseous cooling were obviated through the use of a liquid cooled garment (LCG). The LCG consists of an outer layer of nylon spandex material which supports a network of tubing. When interfaced with a liquid cooling system, the LCG is the primary means by which the crewman is cooled during the performance of EVA. The 4.6 pound garment covers the torso, legs, and arms and circulates water at a flow rate of 240 lbs/hr. The termperature range, controlled by the astronaut, is 45° to 70°F.

The North American Rockwell study (1968) reported the current state-of-the-art and the needed research and technology for life support system subsystems. These data are summarized below in Table 4-4.

TABLE 4-4

LIFE SUPPORT SUBSYSTEMS - CURRENT AND RESEARCH AREAS

SUBSYSTEM	REQUIREMENT	STATE-OF-THE-ART	CURRENT WORK	NEEDED WORK
Oxygen Supply	- 4 hours EVA - 2000 Btu/hr	- Rechange—from supercritical storage	- High pressure store and transfer	- cyro transfer - chemical factors
CO_2 Removal	- maintain partial pressure of 7.6 mm Hg	- LiOH	- metal oxides - selectivity permeable membranes	- molecular sieve
Thermal Control	- reject astronaut & equipment heat load (10,000 Btu)	- H_2O transport and sublimation	- radiator heat rejection - heat pipe transfer	- space radiator - heat pipe

Characteristics of the life support systems are presented in Table 4-5. This table presents systems which are operational, including Gemini and Apollo (missions 11 through 15), systems in the design phase (Apollo 16 through 20 and AAP), and those in the research stage (Advanced Portable Systems)

4.4 WORKSITE TECHNOLOGY

A worksite is a location where an EVA astronaut remains stationary for some period of time to perform specific

TABLE 4-5 CHARACTERISTICS OF EVA LIFE SUPPORT SYSTEMS

EVA Life Support System	O P E R A T I O N A L				D E S I G N		R E S E A R C H		
	GT - IV	GT - IXA - XII	Apollo 9, 11, 15		Apollo 16 - 20	A A P			
	Ventilation Control Module (VCM)	Extravehic. Life Support System (ELSS)	Portable Life Support System -6 (PLSS)	Oxygen Purge System (OPS)	-7 PLSS	Astronaut Life Support Assembly ALSA	Secondary LSS (SLSS)	Portable Environment Control System (PECS)	Optimized PLSS
O_2 Supply	Umbilical	Umbilical	Self-Contain	Self-Contain	Self-Contain	Umbilical	Self-Contain	Self-Contain	Self-Contain
Mounting	Chest	Chest	Back	Top of PLSS	Back	Chest (pressure control unit)	Back	Back	Back
Pressure	3.9 ± .3 PSIA	3.7 PSI	3-4 PSI	3-4 PSI	3-4 PSI	.3 PSI	3-4 PSI	3-4 PSI	3-4 PSI
Flow Rate Lb/hr.	8.2	5.1 or 7.8		8					
Weight lbs.	7.75	42	84	42	103		65-70	102	140
Volume in ^{3}	250	1350	5100	1400		PCU 720 LOP 468		3564	4700
Backup	9 min. self-contain flow rate 2 lb/hr	30 min self-contained	OPS 30 min.	None	OPS 30 min.	Emergency oxygen pack 30 min.	1½ hr.		1.5 hr. at 1600 BTU/hr
Cooling	Gaseous flow	Gaseous flow	LCG 240 Lb/hr 45-70° F	LCG	LCG	LCG	LCG	LCG	
Umbilical	25 ft. lg. 3/16 in. ID 11/16 in OD tensil load 400 lb.	GT IXA & XII 25 ft. GT X-50ft GT XI-30 ft	NA	NA	NA	60 ft	NA	NA	Optional
Metabolic Capability BTU/hr.		1000-71 min 1000-86 min 2000-10 min	1000-3 hr. 1200-4 hr. 4800 BTU		6400 BTU Total	2000 2500 peak	1600 for 2 hrs.	2000 for 4 hrs. 8000 BTU total	1600 BTU/hr for 6hrs. peaks of 2500 BTU/hr

operations. Requirements associated with this site are presented in Table 4-6.

Two general classes of sites can be identified--prepared and unprepared. Unprepared sites refer to the location where an astronaut terminates translation activities to perform a planned EVA function. The location of the unprepared site may or may not be predetermined; if not, it is selected by the astronaut during EVA. A prepared site constitutes one in which site location and EVA astronaut operations in the site are established during equipment design. The site contains all lighting aids, restraint systems, and controls and displays required by the astronaut to perform worksite activities. Examples of prepared and unprepared worksites for operational, design, and research missions are presented in Table 4-7.

Equipment required by an astronaut at a worksite, either prepared or unprepared, can be identified in terms of the FSAS subsystems active at the site. All subsystems will be active with the exception of translation. Table 4-8 lists the equipment associated with each subsystem for the unaided manual EVA FSAS class. The following sections contain descriptions of the state-of-the-art and advanced research requirements for each equipment item, except for suits and life support systems, described in Sections 4.1 and 4.2, respectively.

TABLE 4-6 EVA WORKSITE REQUIREMENTS

SITE ACTIVATION - PREPARATION REQUIREMENTS	SITE ENTRY/EGRESS	SITE OCCUPANCY REQUIREMENTS	SITE LOCATION REQUIREMENTS	TYPE OF SITE OPERATIONS	STABILIZATION REQUIREMENTS
• Type of Activation Remote Local – pre-entry Local – post-entry • Operations Activation of light sources Configuration of structures Selection of operational modes Decision to enter site	• Clearance of Entry Whole body Limb Encumbered – unencumbered • Provisions for Emergency Escape • Safety Hazards Around Entry Protuberances Moving parts Unstable structures Sensitive areas • Visibility of Entry Color coding of translation aids – handholds, feet restraints Lighting of entire entry way Lighting of worksite within entry • Body Orientation to Entry-Way at Entry Always head first or frontal Sideways entry is acceptable if entry-way and worksite are in the field of view during actual entry • Umbilical Dynamics	• Duration • Frequency – number of times during one EVA and during one mission • Number of similar sites	• Type of Location Whole body in free space Body partially in free space – partially in confined space Within unpressurized vehicle Transportable site – as an end of serpentuator or portable • Relationship to Vehicle Immediately adjacent to vehicle structures Removed from vehicle Line of site or hidden	• Visual Inspection Survey Monitoring Equipment operation Astronaut activities Search • Visual/Motor Construction – assembly Alignment Calibration Checkout Static Dynamic Loading – unloading Vehicle configuration – modifying structures Vehicle stabilization Data acquisition/recording Experiment operation Removal/replacement of samples – package handling Maintenance Preventive -servicing Corrective -fault detection -fault isolation -removal/replacement -repair	• Type of Stabilization Restraint Handhold/foothold Both restraints and hand/foothold Cage Portable or fixed • Restraint Location Waist Foot Other body attachment (chest, knee, etc.) • Restraint Type Rigid Flexible Rigidized Retractable – spring loaded • Handhold/Foothold Characteristics Length Hand/foot clearance Location Relation to restraints • Restraint Fastener Quick disconnect Positive feedback of activation • Restraint Adjustments Disconnect/connect Tighten/loosen • Safety Considerations Backup tether Restraints – footholds don't themselves become hazards
MOBILITY REQUIREMENTS	**LIGHTING**	**ASTRONAUT/WORKSITE INTERFACE**	**CONTROL/DISPLAY REQUIREMENTS**	**EQUIPMENT MOUNTING REQUIREMENTS**	**FORCE REQUIREMENTS**
• Motions Required in Worksite Whole body Rotational Translational -lateral -front-back -up-down -twisting Limbs Direction of motion Range of motion • Extent of Motion • Frequency of Motions	• Type Body mounted Wrist Helmet Chest Handheld Removable Fixed • Number of Lights • Location of Lights • Field of View • Brightness • Avoidance of Glare • Color • Adjustments Direction Brightness Field of view size Number of lights Location • Power Requirements	• Type of Site Unconfined Semi-confined Confined Limbs Whole body -body clearances -presence of protuberences • Astronaut Orientation Body axis parallel to main axis of site Body axis perpendicular to main axis of site Body axis off-set from main axis of site	• Nominal Operational Location Size Type Operating characteristics Number Illumination Labelling Orientation Relation of controls to displays • Contingency Operation Alarms Malfunction detection Fault isolation Checkout	• Umbilical Secure • Temporary Storage of Equipment Tools Samples Data recording equipment	• Type of Force Sustained Impulse • Direction of Force Up/down Lateral Fore/aft Rotational • Magnitude of Force • Counter-forces

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FOLDOUT FRAME 2

FOLDOUT FRAME

FOLDOUT FRAME 2

TABLE 4-7 PREPARED AND UNPREPARED WORKSITES

MISSION	PREPARED		UNPREPARED
Operational	Work Site	Activities	Activities
GT – IV	Gemini hatch	16 mm camera installation. Umbilical guard installation.	
GT – IXA	Gemini hatch	Handrail deployment. S012 micrometeorite package retrieval.	Velco hand-pad evaluation.
	Adapter section	AMU donning	
GT – X	Gemini hatch	S012 retrieval	N_2 line disconnect. S010 micrometeorite package retrieval at GATV. T017 micrometeorite experiment installed at GATV.
GT – XI	Gemini hatch	UV stellar photography	Tether attachment
	Adapter	Foot restraint evaluation	
GT – XI	Gemini hatch	UV stellar photography. Synoptic terrain photography. Handrail deployment.	
	Target Docking Adapter	Tether attachment. Evaluation of work tasks. Retrieval of S010.	
	Adapter	Evaluation of work tasks.	
Design			
ATM	Airlock module Center end Sun end	Film handling – loading. Film retrieval – replacement. Film retrieval – replacement.	Temporary storage of sun end film magazine. Connection of translation rail. Contingency deployment of diagonal strut. Astronaut rescue emergency.
Research	Depends on functions to be performed.		

TABLE 4-8

SUBSYSTEM EQUIPMENT FOR
UNAIDED MANUAL EVA FSAS CLASS

SUBSYSTEM	EQUIPMENT	TYPE OF WORK SITE	
		Prepared	Unprepared
Environment Control	Suit Life support	—	—
Stabilization	Body restraints Equip. restraints	Fixed Fixed or struc.	Handrails-portable hand/foot holds Portable
Control	Controls & display	Fixed	—
Actuation	Tools Hand-held equip.	Stored at site Stored at site	Carried to site Carried to site
Support	Lighting Umbilical guards Tethers Guards	Fixed or portable Fixed Attach points fixed Fixed	Fixed or portable Fixed or portable Attach points portable Portable

4.4.1 Body Restraints

The difficulties encountered by the EVA pilot in Gemini XI while attempting to secure a tether between the spacecraft and the Gemini Agena Target Vehicle (GATV) pointed up the need for body stabilization while performing activities at a work-site. For most activities performed at a worksite, body orientation and stabilization are critical for performance and safety. Means must be provided to enable the astronaut to apply required forces and counter-forces and make required motions and movements in the most effective and safe manner. These means usually include the use of body restraints.

Restraint systems may be classified in terms of the method by which they are fixed at a site or portable, in terms of rigidity or flexibility, or in terms of the body attach point or points (i.e., waist, feet, etc.)

As pointed out in the North American EVA study, the choice of restraint systems to stabilize an astronaut at a worksite depends to a large degree upon the nature of the work tasks. In some cases sufficient restraint may be provided by handholds alone; other tasks may require stabilization of the pilot to enable him to exert two-hand forces of 25 to 50 pounds. Two point restraint may include attachment to a handhold of the astronaut's waist or hips. Three point systems may add foot restraints (North American, 1968).

Restraint design characteristics and descriptions are presented below for three phases of development: operational, design, and research.

OPERATIONAL RESTRAINTS

Gemini IXA

At the AMU workstation located at the adapter section of the spacecraft, two cylindrical handholds 1.39 inches in diameter were installed to assist in the AMU donning operation. Foot stirrup restraints were also used to stabilize the astronaut during the AMU donning but were found to be inadequate for that purpose. The astronaut's feet kept slipping out of the stirrups as he maneuvered to don the AMU.

Flexible velcro-backed portable handholds were evaluated as restraints and as maneuvering aids. Eighty patches of nylon velcro were hooked onto the surface of the spacecraft to engage the nylon velcro-pile pads of the handholds. Results of the in-flight evaluation indicated that the contact forces were insufficient for controlled maneuvering or body attitude but were adequate for holding a stationary position.

Gemini X

Other than the rectangular handrail used for translation, the only restraint employed in this EVA was the strap used in stand-up EVA. The worksite for S010 micrometeorite package retrieval was so unprepared that the astronaut had to use bundles of wires and struts as handholds. Retrieval of the S010 experiment package was accomplished without difficulty, but the pilot elected to discard the replacement package rather than risk losing the one he had just retrieved.

Gemini XI

For the EVA to be accomplished on this mission, molded overshoe foot restraints (custom fitted to the feet of the astronaut) were installed at the adapter worksite. These restraints enabled the astronaut to apply forces in excess of 25 pounds.

Fixed handholds were installed at the GATV worksite behind the docking cone. These handholds were 6.5 inches long, one inch in diameter, and had 1.5 inches of hand clearance.

Gemini XII

At the Target Docking Adapter worksite at the GATV, waist restraints were installed. The astronaut connected the restraints and evaluated restraint capability to control body position while he rested. While in the waist restraints at the TDA, he performed the Gemini-Agena tether attachment task which had been so difficult for the unrestrained Gemini XI astronaut.

The astronaut evaluated portable handholds at the adapter section including the "pip-pin" and velcro designs. The pip-pin handhold/tether attachment device was comprised of an anodized aluminum handhold and insert consisting of a conventional "pip-pin" mechanism with ball detents for attachment to the spacecraft. A spring loaded pushbutton actuator was depressed to retract the balls before the device could be installed or removed. The pins were 3 inches wide and included a loop with an inside diameter of 1.75 inches for tether attachment. When the rotational freedom of the devices was removed, they made excellent handholds, helped to control body attitude, and were useful as waist tether attachment points. "Pip-pin" antirotation devices were installed over 11 of the attachment holes. Without these devices the pins were free to rotate and would do so when any torque was applied. Seven of these devices were used in Gemini XII.

The velcro backed portable handholds used in Gemini XII consisted of four trowel shaped, rigid devices. The handholds were 6.5 inches in length and 1 inch in diameter. Each was equipped with a tether attachment ring 1.5 inches in diameter. Polyester velcro hooks were located on built-up flat surfaces in four places on the target vehicle to engage the pile of the handholds. Based on analysis and simulation, it was concluded that fixed handholds are superior to portable, and that portable handholds should be provided only when fixed holds cannot be installed.

Three fixed handholds coated with a resilient friction material were provided on the back of the GATV docking cone for restraint during tether attachment, and two similar handholds were provided on the back of the cone. The handholds were 6.5 inches in length, 1 inch in diameter, with a 1.5-inch clearance from the surface.

The molded foot restraints located at the adapter worksite proved far superior to all other restraints evaluated. In these "Dutch Shoes" the astronaut applied forces in excess of 25 pounds and performed the electrical connection and cutting tasks. He was ablt to lean backward nearly 90°, roll nearly ±45° and yaw almost 90°. The size of the boots was 21 by 13 by 4 inches.

RESTRAINTS IN DESIGN PHASE

Restraints to be used in AAP include handholds and handrails. The rail configuration is confined within a cross-section envelope of .62 by 1.25 inches and with a 2-inch standoff.

The primary restraint system to be employed on the ATM mission at film retrieval worksites includes the foot restraint or Dutch Shoes and handholds. When equipment-to-astronaut tethers are required, a wrist tether has been recommended (Ekstrom, 1969).

In a report concerning the current status of ATM EVA system concept development prepared by the Matrix Research Company (Brown and Hayes, 20 November 1969), the following requirements and design approaches are presented for body restraint systems:

- Restraint release mechanisms shall be of the quick-action type, designed for one-hand operation.
- Restraint systems shall incorporate redundant release methods.
- Dutch Shoes will be of a universal size or the A7L-B suit will have a standard size overboot.
- Dutch Shoes may be designed to enable the astronaut to reposition his body.
- When the astronaut's feet are secured in the Dutch Shoes and handholds are provided, a waist restraint is not required.

RESTRAINTS IN RESEARCH PHASE

Restraint Research and Evaluations

A large amount of research data is available on the effectiveness of various types of restraints for representative EV functions. General Electric reported results of a neutral bouyancy study to measure the effects of restraint systems on impulse and sustained force-producing capabilities of astronauts in zero gravity (1967). An impulse force represented a peak force for one-second duration, and a sustained force represented the minimal force applied over a four-second interval. The directions of force application examined included push-pull, left-right, and up-down, and ranged from 11.7 to 20.8 pounds for sustained force and from 23.4 to 51.5 pounds for impulse force.

Restraint conditions studied were single point (handhold, waist, and Dutch Shoes), two point (handhold and waist, handhold and shoes, and waist and shoes), and three point (handhold, waist, and shoes). Results of the study indicated that an astronaut in zero gravity cannot sustain an exerted force in a no-restraint condition. The best restraint system in terms of maximum forces for force types and directions are presented below:

- <u>Sustained Force</u>
  - Single point restraint
    - -waist best for push-pull
    - -shoes best for up-down
    - -handhold best for left-right
  - Two point restraint
    - -handhold and shoe best for up-down and left-right
  - Three point restraint
    - -best of all conditions for push-pull

- <u>Impulse Force</u>
  - Single point
    - -less desirable
  - Multiple point
    - -handhold and shoe, greatest force in all directions
    - -handhold and waist, poorest multiple point system

A follow-up study by General Electric (Human Engineering Criteria for Maintenance and Repair - HECMAR, 1969) investigated the effects of restraint systems on reach envelopes and package handling. Results of the reach envelope study conducted in neutral bouyancy in suited and unsuited conditions indicated that:

- Handholds provided the largest range of motion envelope but the poorest stabilization. Use of handholds was recommended for gross, low force, short duration tasks.

- Waist restraints were found to eliminate hip, knee, and ankle motion potential and provided a limited reach envelope.

- Dutch Shoes afforded a large access envelope below the referent (chest) height.

The assessment of effects of restraint system design on package handling involved suited subjects removing and replacing packages of six sizes and masses (weights ranging from 50 to 235 pounds) under each of these five restraint conditions:

- Handhold

- Dutch Shoe

- Rigid waist

- Handhold and rigid waist

- Handhold and shoe

Results indicated that the Dutch Shoe is the optimal restraint for the package handling situation. Use of handholds alone led to longer module cage times and generally provided insufficient stability for task performance. In many cases, loss of body control increased as body distance from the handhold was increased. Use of waist restraint and waist and handhold prevented task performance for front module removal/replacement. The rigid positioning of the waist restraint also restricted the reach envelope.

A third experiment reported in the HECMAR report was concerned with maximum reach envelopes across restraints and the ability to perform useful work within the envelopes developed in the first reach envelope study. The task used was a stylus hand-steadiness test. Results indicated that Dutch Shoes afforded the maximum physical reach and acceptable motor performance. Waist restraints requlted in limited reach and acceptable motor performance. Handholds alone led to degraded performance.

A study performed by Wortz _et al_, Garrett Corporation (1969), evaluated the effects of four restraint conditions on such operations as removal-replacement, connect-disconnect, lever push-pull, bolt torque, and wheel turning. Restraints studied were:

- Gemini XII Dutch Shoes with two waist straps
- Gemini XII Dutch Shoes with one waist strap
- Cage (enclosing lower portion of body--waist down)
- Rigid leg restraint - pivotable

Results of the investigation indicated that, in terms of time to perform tasks, the shoes and single strap were best. Metabolic rates were greater with the cage restraint and did not differ among other conditions. The cage was considered the best overall restraint. Forces applied in this study included impulse forces (.1- to .3-second duration) and sustained forces (up to 55 seconds).

An evaluation of restraint systems was conducted by the EVA pilot on Gemini XII. During this EVA period the following observations were made:

- Waist restraints alone provided a comfortable resting position.

- The astronaut stated that the foot restraints gave the best freedom of action.

- Velcro portable handholds did not provide sufficient stabilization.

- The Saturn bolt removal/replacement was judged easy with the foot restraints and moderately difficult with the waist restraints. The waist restraint attach points were judged to be far from optimal, and the right waist tether interferred with operations. The bolt workspace was judged to be too close using the waist tethers.

- Making and breaking electrical connections with one hand and both hands was performed easily with the Dutch Shoes and with more difficulty with waist restraints.

<u>Rigidized Tether</u>

An advanced restraint concept currently undergoing analysis is the variable flexibility tether system (Rader, 1968). This system comprises a flexible tether which is rigidized by means of ball socket links strung over a central cable which can apply tension to the links. For the development test article, the length of the tether is 8 feet, and the diameters of the ball and socket are 2 inches and 2½ inches, respectively. The system includes three components: 1) the tether section with a maximum diameter of two inches and minimum diameter of one inch; 2) the proximal controller located on the astronaut's left hip which applies tension to the central cable, the manipulator actuator, and the proximal distal disconnect; and 3) the distal end attachment (disconnect or manipulator) which can be operated independent of tether rigidity. The prototype system weighs 16.6 pounds. Laboratory testing indicates that the maximum movement of restraint is 40 to 60 inch-pounds. This is felt to be insufficient for most expected work situations. Further development will include investigation of other joint concepts to increase rigidity and use of electrical devices for tension application (North American, 1968).

Rigid Restraints

Provision for rigid waist restraints have centered on telescoping devices of variable length with the capability of being locked in position. Rod connectors to the astronaut and to the spacecraft are usually free rotating, and the astronaut counteracts the tendency to rotate through use of leg muscles.

Alternate concepts for rigid restraints incorporate sliding bars to enable the astronaut to assume different positions. The restraints are rigidized by a tension lever which locks both the ball joint at the waist and the position of the slide bar (North American, 1968).

STEM

One special case of rigid restraint is the Storable Tubular Extendible Member or STEM. This device consists of a tape or element of thin metal which assumes a tubular shape of high strength when extended. It is stored in minimum space when coiled in the flattened condition on a spool, as shown in Figure 4-1.

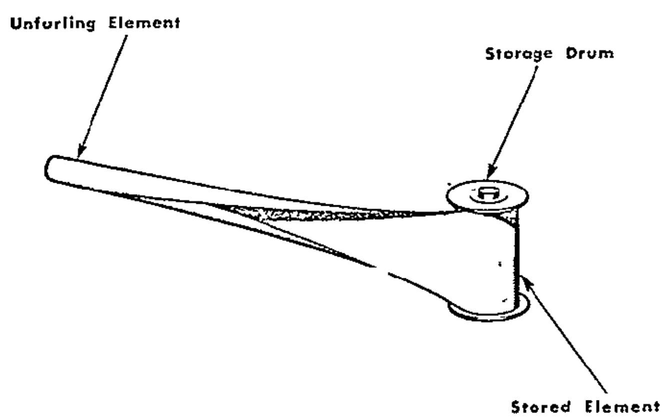


FIGURE 4-1 STEM CONCEPT

The spool diameter is chosen so that the elastic limit of the tape material is not exceeded when coiled. In this manner, no permanent strain is introduced in the tape thus guaranteeing that it returns to the tubular form after repeated extension/retraction cycles.

The STEM has been designed and produced by Spar Aerospace Products LTD. as an antenna boom and has been used in Gemini as a boom for the radar transponder antenna, UHF antenna, and a boom for the magnetometer experiment deployed from the spacecraft. Its potential use as an easily-adjustable, rigid, astronaut restraint has been recognized by its manufacturer. A preliminary concept has two STEM members deployed from behind the astronaut over each shoulder and one deployed between his legs. The other end of each member adheres to the structural surface at the worksite. The length of each boom is adjustable, and the maximum distance for body/work surface separation is 2.75 feet (Haines et al, 1967). Each boom must be capable of withstanding a minimum of 100 pounds of force. A description of capabilities of selected STEM devices is presented in Table 4-9.

Portable Restraints

Many of the restraints discussed above are being developed or have been developed for use at a prepared worksite where pre-positioned attachment points are included in the site design. The requirement for pre-positioned points is not as limiting for the variable flexibility tether which can use vise grips and for the STEM which can use adhesive attachment or grips. As indicated by North American (1968) some of the most beneficial EVA will be performed at unprepared sites where attach points are probably not available. A requirement, therefore, is to enable the EVA astronaut to furnish his own attach points.

Advanced concepts for portable handholds, portable tether attach points, and maneuverable foot restraints are currently being developed for the orbital workshop by McDonnell Douglas. Artist concepts of this equipment appear in Figures 4-2 and 4-3.

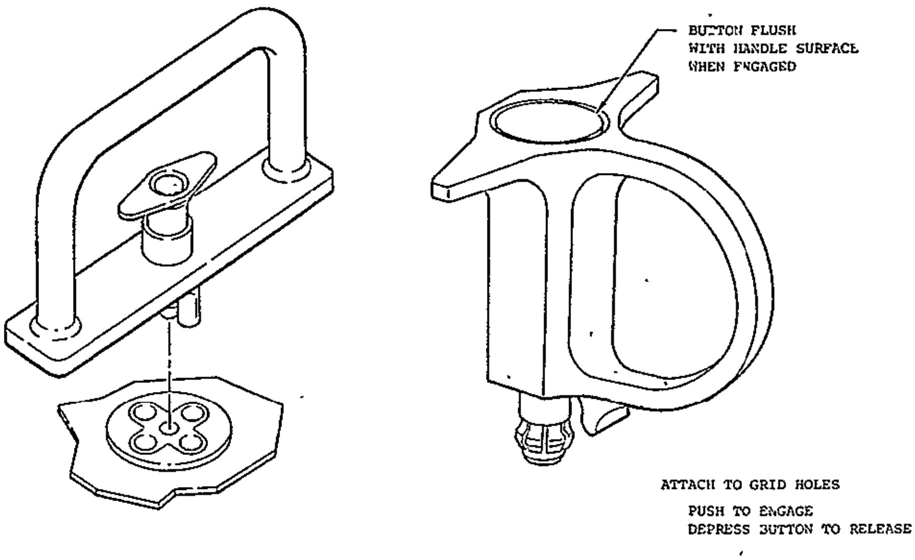
TABLE 4-9

STEM CAPABILITIES

STEM Designation	Length	Bending Movement	Size (inch)	Weight	Power	Rate of Extension
Antenna A-18	60 ft.	6-in.-lbs	5.6 X 3.0 X 2.8	1.5 lb	6W	.9 in/sec
TDM Antenna	60 ft.	8-in.-lbs	4.2 X 2.5 X 2.5	1.25 lb		4 xec total
Tele-Stem Boom	83 in.	265-ft.-lbs	4 X 6.2 X 24.4	12.65 lb		5 in./sec
STEM Boom	150 ft.		4.4 X 3.4 X 8.9	3.9 lb*		3 in./sec
Bi-STEM	40 ft.	750-in.-lbs	5.2 X 5.3 X 11	5-5.8 lb*	20W	4 in./sec
Manually Deployed	10 ft.	250-in.-lbs	9.2 X 2.9 X 2.7	1.75 lb	None	Manual

(From "STEM - A Profile", SPAR AEROSPACE, Ontario, Canada)

* less tape



a. Handhold b. Tether Attachment

FIGURE 4-2 HANDHOLD AND TETHER ATTACH POINTS

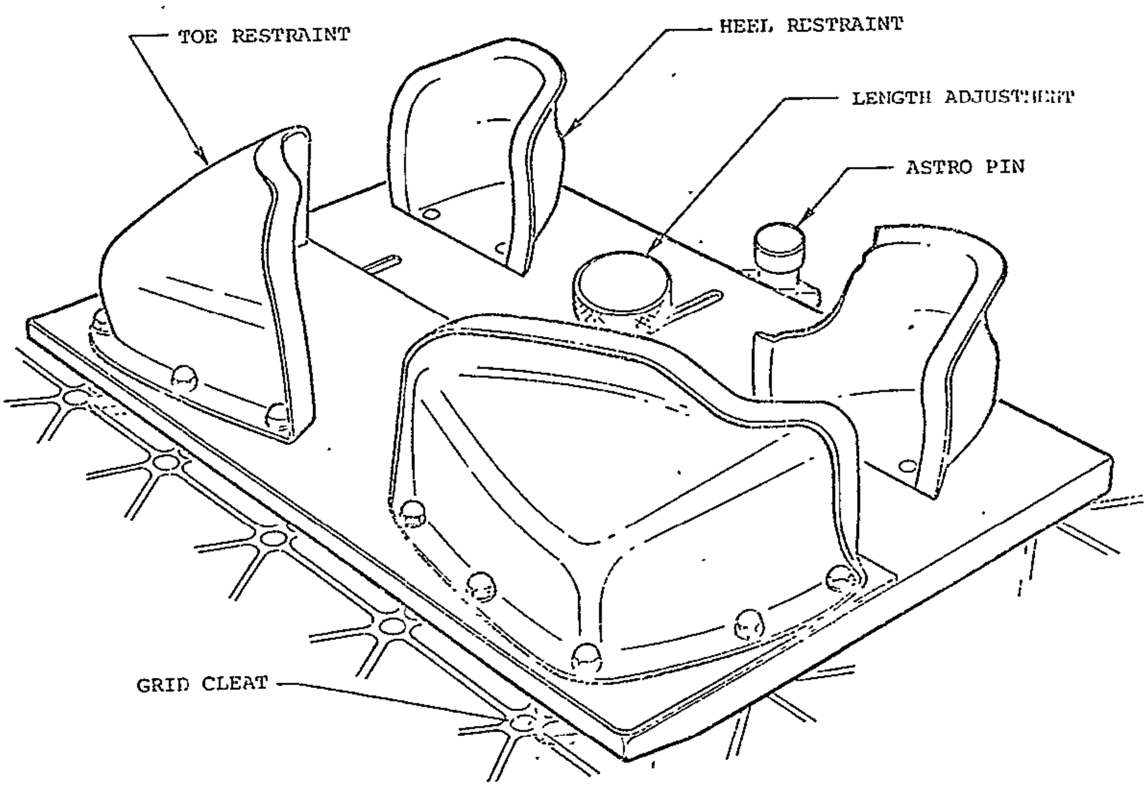


FIGURE 4-3 PORTABLE FOOT RESTRAINT

The summary of current developments and needed research, as determined by North American Rockwell, is presented in Table 4-10. An evaluation of restraint concepts is included in Table 4-11.

TABLE 4-10

RESTRAINT TECHNOLOGY SUMMARY

SYSTEM	REQUIREMENTS	STATE-OF-THE-ART	CURRENT WORK	NEEDED WORK
Foot Restraints	Restrain at site Allow for repositioning	Dutch Shoes S-IVB Workshop Grid floor	None	Angular repositioning Decreased weight Portable system Grid floor study
Variable Flexibility	Provide waist restraint Ease of attachment & repositioning 25-50 lbs force	Prototype GE	GE	Increased loads Decreased weight
Rigid Waist	Ease of attachment & reposition 25-50 lbs force	Telescoping rods	STEM & Bi-STEM	Rods variable between 1-3 feet Easily operable STEM

As described in the conclusions concerning restraints in the summary of Gemini EVA, the use of proper body restraints is necessary to assure the success of an EVA mission. The extravehicular experience accumulated in the Gemini Program indicated that thorough analysis and accurate simulation for EVA must be conducted and that body restraint requirements indicated by the analysis and the simulations must be satisfied.

TABLE 4-11 EVALUATION OF CURRENT RESTRAINT CONCEPTS

RESTRAINT SYSTEMS	GEMINI	FORCE APPL. G.E. 1967	HECMAR WORK-REACH	HECMAR CARGO HANDLING	NORTH AMERICAN	SITE OPERATIONS GARRETT	A A P	DOMINENT PROBLEMS
FIXED RESTRAINTS								
o Single Point								
handholds	useful	left forces good	poor stab. good reach	poor – time			in design	stabilization
waist	GT XII interference	push–all good	limited reach	interference				attack points
foot restraints	GT XII–best	up/dwn good	good reach	best			in design	repositioning
wrist							recommended	interference
o Dual Point								
handhold – shoe	GT-XII satisf.	up–down right–left					in design	pull–push force
handhold – waist	GT-XII satisf.	poorest impulse						any force
shoe –waist						good – time		attack points
o Three Point								
handhold–shoe–waist		best suit						structures
o Cage					not sufficient	best		sizing
o Variable flexibility					inadequate force			forces
o Rigid waist					rotational problems			adjustments
o STEM					feasible		feasible	operations
PORTABLE RESTRAINTS								
o Flexible velcro	poor stability							
o Rigid velcro	poor stability							stability
o Pip pin	adequate							
o Triangular shoe					feasible		in test	

During EVA restraints must be provided both for rest and for work tasks.

The following restraints were found to be most satisfactory in the Gemini Program:

- Foot restraints as used on Gemini XII for rest and localized work
- Waist tethers as used on Gemini XII for rest and localized work (slightly greater freedom of movement was possible with waist tethers than with foot restraints)
- Rectangular handrail for transit across a spacecraft surface
- Pip-pin devices for combination tether attachment points and handholds where flush-surface installations were required
- U-bolts for simple attachment points where flush-surface installations were not required

4.4.2 Equipment Restraints

When the EVA astronaut must handle packages and equipment at the worksite, some means of attachment must be provided to secure the items when they are not actually in his hands. Equipment restraint technology is described below for the operational, design, and research development stages.

OPERATIONAL RESTRAINT PHASE

Package handling on Gemini EVA missions was largely limited to the removal/replacement of the S010 micrometeorite experiment package at the spacecraft hatch worksite and the S012 package at the Gemini Agena Target Vehicle. The S010 package was handled on Gemini missions X and XI while the S012 was removed on missions IX and X. The fact that no back-up equipment tethers were used on these missions led to the loss of the S012 during Gemini X EVA. In this EVA period the pilot also lost an untethered 70 mm still camera. In an assessment of neutral bouyancy simulation in support of Gemini missions, Trout, et al (1969) concluded that a lanyard is required to prevent the loss of equipment being handled by the astronaut. Such a lanyard was included on Gemini XII to secure cameras.

The primary equipment attachment device employed in Gemini was velcro. Packages and cameras were provided with velcro strips which were attached to velcro hooks on spacecraft surfaces or on the ELSS chestpack. Pen lights used to illuminate the work area at the adapter worksite were connected to handholds by velcro. At the adapter worksite, the Gemini XII pilot performed an evaluation of hook and ring sizes for semi-permanent equipment retention.

EQUIPMENT RESTRAINTS IN DESIGN PHASE

In developing the man/systems integration and human factors requirements for ATM EVA (Brown and Hayes, 1969), the following requirements have been identified for equipment restraints/tethers:

- Tethering of equipment is not required when hard locks are provided or when transferring equipment from one locked location to another, if both hands are available. Tethering of equipment is required in all other conditions.

- Equipment tethering techniques to be considered include:
  - Wrist tethers
  - Waist tethers
  - Locks to fix the equipment to structures
  - Telescoping tethers either attached to the crewman or to structures.

EQUIPMENT RESTRAINTS IN THE RESEARCH PHASE

The current and required development of efforts for equipment restraints was described by North American Rockwell (1968). As described in that report, the manner in which temporary restraint of equipment at a worksite is performed depends on two factors: the weight of equipment and the state of preparedness of the worksite. The four types of equipment restraint described were fixed mechanical, mechanical latch, velcro, and adhesive.

Fixed Mechanical

Used at prepared worksites, this type of restraint is characterized by lugs on the spacecraft surface and on the equipment and a "pip-pin" inserted to join the two. The operation requires use of both hands.

Mechanical Latch

This restraint includes concepts such as special purpose latches to completely encircle and grip and general purpose vise-grip designs associated with the variable flexibility tether.

Velcro Patch

The velcro patch provides light restraining forces for temporary restraint of equipment. Hooks or pile must be pre-installed at the worksite and the opposite material installed on the equipment. The material is very weak in peal but requires only one-handed operation.

Adhesives

Adhesives for temporary restraint of equipment may be classified into three concepts: encapsulation, exothermic chemical heating, and electrical heating. A major advantage of adhesives is that operations can be performed at unprepared sites as effectively as at prepared sites. Application time is 30 seconds.

Encapsulated adhesive systems require the astronaut to rupture the capsule and form the bond. Achieved bonding strengths greatly exceeded 100 PSI. Exothermic compounds, which require electrical ignition, provide a fixed amount of heat to the adhesive. Tensil strengths in excess of 100 PSI have been measured. Electrical heating is used to bring the adhesive to a preselected temperature. Strengths of 50 PSI have been recorded.

Table 4-12 summarizes the North American Rockwell data for equipment restraints including current and needed research.

TABLE 4-12

SUMMARY OF EQUIPMENT RESTRAINT TECHNOLOGY

SUBSYSTEM	REQUIREMENT	STATE-OF-THE-ART	CURRENT WORK	NEEDED WORK
Fixed mech. pin Mech. latch	Rigid 80-lb restraint Rigid 40-lb restraint	"Pip-pin" mating logs Vise grip pliers	None Vise grip update	Standardization Standardization modification
Velcro patch	1-hand attachment for 10-pound equipment	Velcro available	Commercial	Improve peel
Adhesive	Rigid 50-pound restraint	Encapsulated Exothermic heaters Electric heaters	Several industries	Further development Application attach point

4.4.3 EVA Tools and Worksite Aids

Worksite aids include controls and displays, lighting aids, and umbilical and body guards. Worksite tools include devices to assist the EVA astronaut in connecting, attaching, assembling, positioning, aligning, installing, removing, replacing, repairing, servicing, cleaning, focusing, calibrating, inspecting, deploying, shaping, tightening, troubleshooting, checkout, and maintaining.

OPERATIONAL TOOLS AND AIDS

Activities completed during Gemini missions which required the use of tools and worksite aids include those listed in Table 4-13.

TABLE 4-13

GEMINI ACTIVITIES REQUIRING WORKSITE TOOLS AND AIDS

OPERATION	MISSION	TOOLS/AIDS
Install umbilical guard at hatch	IV	Umbilical guard.
Route umbilical through guide	XII	Umbilical pigtail
Place umbilical in clip or handbar	XII	Umbilical clip
Position debris cutters	IX A	Cutters
Cut two strands of cables	XII	Cutters
Perform torquing of fixed bolts	XII	Wrench
Remove-replace Saturn bolt	XII	Wrench
Connect-disconnect connectors	XII	Electrical & Fluid Quick Disconnect
Attach tether to Agena XI	XII	Tether Clamp
Evaluate camera placement-in-hatch	XII	Tethers
Deploy penlights at adapter	IX A XII	Lights
Connect tether hooks at adapter	IX A XII	Tether Hooks

In terms of the EVA functions developed in Section 2.0, those functions performed on Gemini missions with characteristics on performance data are presented in Table 4-14.

TABLE 4-14

FUNCTIONS PERFORMED DURING GEMINI MISSIONS

FUNCTION/TASK	MISSION	REQUIREMENTS	PERFORMANCE	
			TIME* (min-sec)	ACCURACY
Deploy				
handrail	XII	Extend the 4-section 99 inch telescoping handrail from hatch	01:55	No Problem
handrail	IX A X XI	Forward 21 inch rail deployed for 1.5 inch clearance		No Problem
Remove/Replace				
S012 package	IX A	Removal of micro-meteorite pkg. from spacecraft exterior		No Problem
S010 package	X XII	Removal of micro-meteorite pkg. Installation of replacement--at Agena Target Vehicle	03:39	Replacement pkg. discarded on GTX stored on chestpack in XII
Film	XI	Change film at spacecraft hatch		No Problem
Inspect				
AMU Connectors	XI A XII	Prior to donning Distinguish & match multi-colored markings		No Problem Difficult

* GT XII, only

TABLE 4-14 (Continued)

FUNCTION/TASK	MISSION	REQUIREMENTS	PERFORMANCE	
			TIME* (min-sec)	ACCURACY
Maintain-repair				
Bolt tightening	XII	$\frac{1}{2}$ & $\frac{1}{4}$ in. fixed bolts &. Saturn bolt-clockwise & counter clockwise	04:50	No Problem in Dutch Shoes
Workstation cleaning	XII	Stowing & retrieval of equipment	2:14	No Problem
Cable cutting	XII	Cut 2 strands of cable-tool evaluation	3:29	No Problem
Assemble				
Install 16 mm camera	ALL	Install EVA camera at hatch GT XII evaluation 3 positions		No Problem
Install umbilical guard	IV XII	Install guard on IV Insert umbilical on XII		
Attach dock bar mirror	IXA	Install mirror at hatch		No Problems
Quick disconnect	XIA	Nitrogen line correction for maneuvering suit		Some difficulties
Tether connect	XI XII	Install wire loop over docking bar and install bar clip to attach tether to bar	02:20	Extremely difficult on XI—no restraints. No problems on XII
Operate-Monitor				
Volume operation	IX A	Oxygen valve on AMU at adapter worksite	01:08	No Problems
Camera activation	XII			Unsuccessful

* GT XII, only

TOOLS AND AIDS FOR MISSIONS IN DESIGN PHASE

No tools are currently being planned for use in the ATM EVA. Worksite lighting and labeling requirements being determined for Marshall Space Flight Center include:

- Type of illumination--artificial or natural
- Number of lights
- Fixed light location
- Light field of illumination
- Spectral composition
- Range of illumination

TOOLS AND AIDS FOR MISSIONS IN THE RESEARCH PHASE

As described by North American Rockwell, current tool efforts include the development by Martin of an integrated tool kit with hand power tool, adhesive applicator, lighting, and power. A series of special attachments is also being developed for power tools. RAFF Analytic Study Associates is determining the requirements for a space mitten, tool mitten, and space-tool mitten in which an astronaut inserts his hand into the tool.

Advanced tool concepts include the use of a versatile power tool used for sawing and wrenching and as a portable power source. Two types of joining will be required: mechanical assembly and welding. Most mechanical assembly operations will be pre-planned with the EVA assembly confined to actuating captive screws, latches, etc.

4.5 ASTRONAUT TRANSLATION/CARGO TRANSFER TECHNOLOGY

Translation of the crewman applies to activities associated with maneuvering from one work station to another. The subsystems of the free space activity system which apply to the translation operation include:

- Translation
- Control of translation
- Stabilization during translation
- Translation support systems
- Life support systems

The only extravehicular function which is completed in the translation mode is cargo transfer. A description of crew translation and cargo transfer technology is presented below.

4.5.1 Astronaut Translation

The translation system technology for operational, design, and research missions is described in the following sections.

OPERATIONAL TRANSLATION SYSTEMS

Translation in Gemini EVA was confined to maneuvering in the vicinity of the egress hatch and moving to worksites located at the adapter (aft) section and/or the Gemini Agena Target Vehicle (GATV). Aided and unaided translation was employed on these missions with the aided mode consisting of the use of a Hand-Held Maneuvering Unit.

Gemini IV

The primary objective of the first U.S. orbital EVA was to establish the feasibility of EVA. A secondary objective was to evaluate the effectiveness of the HHMU as a translation aid. The HHMU consisted of two 1-pound tractor jets and one 2-pound pusher jet to provide six degrees of freedom in movement (three rotational-motion axes for stabilization and attitude control and three translational-motion axes). Accelerations were .3 feet/second^2 maximum and rates were 80 degrees/second^2 for yaw, 20 degrees/second^2 for pitch and roll. Total available thrust time was 20 seconds with a delta velocity capability of 6 feet/second. The entire unit weighed 7.5 pounds, and required forces for trigger actuation were

15 pounds pre-load and 20 pounds at maximum displacement. Maximum range of the unit was 50 feet. The concept is depicted in Figure 4-4.

FIGURE 4-4 HAND-HELD MANEUVERING UNIT

After performing the HHMU evaluation, the EVA pilot assessed tether dynamics. The tether-umbilical employed was 25 feet long and caused the pilot to move back in the general direction of the spacecraft. It provided no means of body control other than limiting the distance between the astronaut and the vehicle.

Gemini IX A

One objective of this EVA was to evaluate the Astronaut Maneuvering Unit (AMU). Due to high workloads and resultant visor fogging problems associated with donning the AMU, the EVA was terminated without the inflight evaluation being accomplished. Therefore, since the AMU cannot be considered an operational EVA translation aid, the characteristics and design approaches for the unit are described in the research section.

During this EVA the pilot used rectangular handrails to traverse the eight feet from the cockpit to the adapter section. These rails were .55 inch by 1.25 inch in cross-section and allowed 1.5 inch hand clearance. The forward rail, extending from the hatch to the retrograde section of the adapter, was 21 inches long. The aft handrail, 46 inches long, was mounted on the adapter equipment section (Figure 4-5).

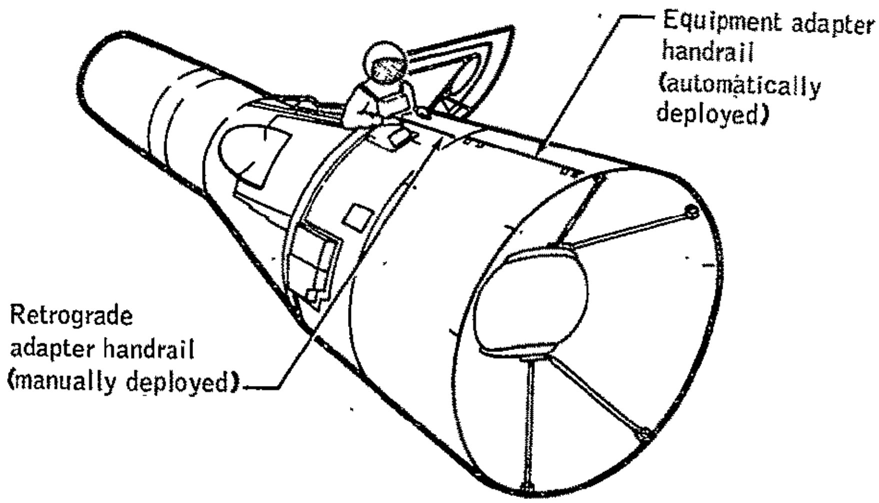


FIGURE 4-5 . EXTENDIBLE HANDRAILS ON SPACECRAFT ADAPTER

Gemini X

Operations performed in this EVA which required translation included retrieval of the S010 micrometeorite experiment package at the GATV, located 5 feet away from the Gemini, and evaluation of an improved HHMU. To reach the unprepared worksite for S010 removal operations, the pilot maneuvered hand-over-hand along the surface of the spacecraft. While maneuvering around the target vehicle toward the worksite, he lost his hold on the smooth lip of the docking cone and drifted away from the target vehicle. He then used the HHMU to translate 15 feet back to the Gemini and maneuvered over the surface again to the worksite using bundles of wires and struts as handholds. Once package retrieval was completed, the astronaut returned to the spacecraft by pulling himself back with the umbilical.

During ingress to the hatch, the pilot became entangled in the 50-foot umbilical. It was noted that the bulk of this umbilical was an inconvenience and made management of the umbilical during translation a problem.

The HHMU used on the Gemini X required trigger forces of 5 and 8 pounds as opposed to the 15- and 20-pound pre-load and maximum forces required for the Gemini IV HHMU. The unit weight was 3 pounds, and the delta velocity capability was 84 feet/second as opposed to the Gemini IV HHMU incremental velocity of 6 feet/second. Characteristics of these two units are presented in Table 4-15.

TABLE 4-15

GEMINI IV AND X HHMU CHARACTERISTICS

CHARACTERISTIC	GT IV	GT X
Thrust-tractor and pusher	0 - 2 lb	0 - 2 lb
Specific impulse (sec)		63
Total impulse (lb/sec)	40	677
Available vel. increment (fps)	6	84
Storage tank pressure (PSI)	4000	5000
Regulated pressure (PSI)	120	125+5
Nozzle area ratio	50:1	51:1
HHMU weight (lbs)	7.5	3
Propellant weight (lbs)	0.7	10.75

Gemini XII

Translation in this mission was accomplished through the use of handrails and handholds. The pilot egressed the hatch and maneuvered over the handrail to the nose of the vehicle, evaluating tether dynamics on the way. The translation took 41 seconds which resulted in a translation rate of .16 fps (Loats et al, 1967). After performing the Gemini-GATV tether attachment and worksite preparation tasks, the pilot translated back to the hatch. After retrieving more umbilical, he translated to the adapter section in 12 seconds. Upon completion of adapter worksite activities, he translated back to the hatch in 31 seconds, and then to the Agena work station in 74 seconds. The final translation from the Target Docking Adapter worksite back to the hatch required 51 seconds. In making the two round-trips between hatch and TDA worksite and the one round-trip between the adapter worksite and the hatch, the pilot was translating for approximately 4 minutes. Some of this time was spent in evaluating tether dynamics and repositioning equipment.

The preferred method of translating using handrails was with the body axis parallel to the rails. In this configuration the pilot was able to use his feet to contact the spacecraft, thus increasing the body stabilization during the translation.

TRANSLATION AIDS FOR CURRENT MISSIONS

In the AAP/ATM mission, translation will be accomplished through the use of a series of handrails and handholds. In a typical film replacement task, the astronaut will egress the hatch located in the Airlock Module (AM) and proceed forward along a single rail; he will then translate laterally to the ATM through the use of various handholds and handrails that are located along the ATM support structure. Translation up the ATM is accomplished through movement along a dual rail to the sun-end work station. Portions of the dual rail system will be hard mounted during launch with the remaining sections being automatically deployed or assembled by the astronauts (Brown and Hayes, 1969).

Besides safety, one prime rationale for the exclusion of propulsive translation aids for ATM EVA is possible interference or contamination of telescope optical systems caused by propellent residue and gases. This factor will need to be considered on most advanced missions where sophisticated optical systems are used. Requirements placed on ATM EVA demand that direct return to the airlock module EVA hatch be possible from either worksite within 15 minutes and that astronaut translation be accomplished independent of film magazine transfer. There is no requirement to tether the EVA crewman to structures while he is translating since the umbilical provides the necessary emergency restraint.

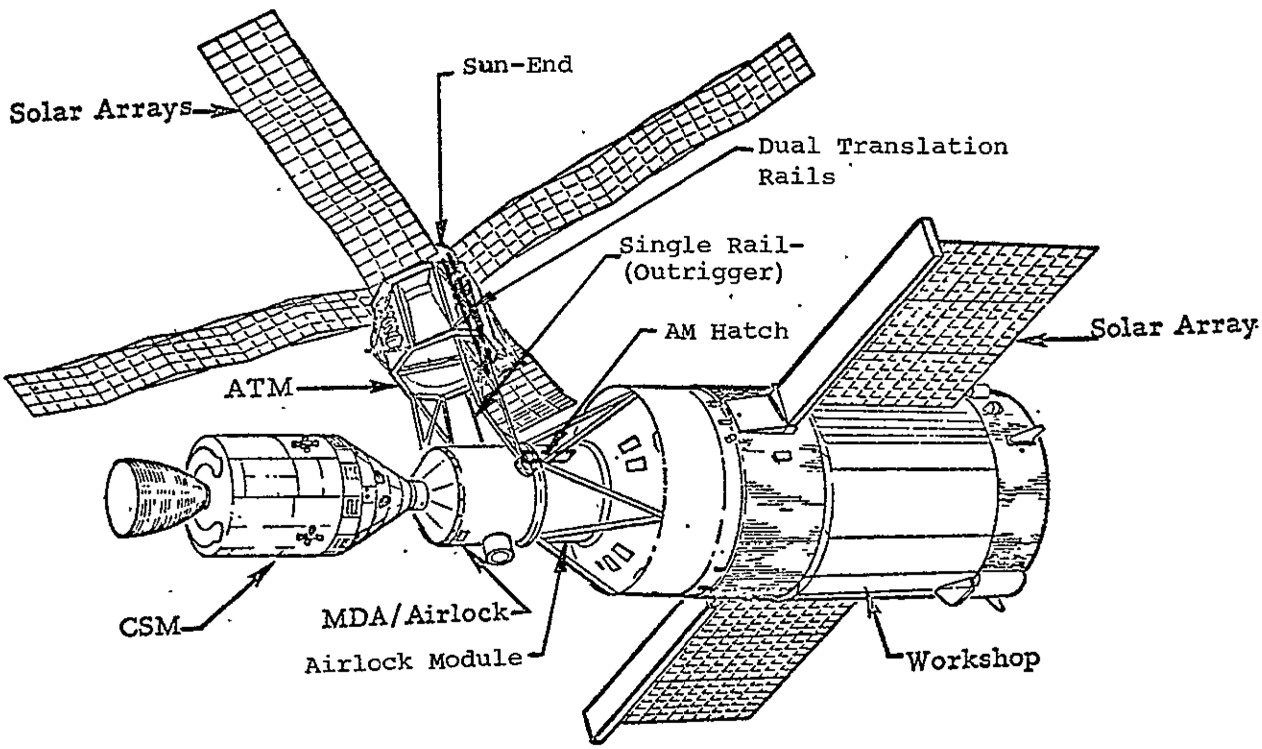


FIGURE 4-6 AAP CLUSTER SHOWING TRANSLATION AID LOCATIONS

TRANSLATION AIDS FOR RESEARCH MISSIONS

Bell (1969) listed some of the situations in which a maneuvering capability would greatly enhance the effectiveness of the EVA astronaut. These include:

- Inspection
  - -Observing an overboard dump
  - -Checking external plumbing
  - -Periodic inspection
  - -Checking for reaction control plume impingement damage
- Maintenance
  - -Repair--e.g., structures
  - -Replacement--e.g., solar array panels
  - -Replenishment
- Operation
  - -Activation or reactivation of dormant vehicles
  - -Resupply of active vehicles
  - -EVA technology development
- Assembly
  - -Support of in-orbit manufacturing facilities
- Rescue
  - -Transfer of additional life support consumables
  - -Retrieval of stranded astronaut
  - -Rapid assistance
- Scientific Experimentation
  - -Mapping plasma wakes, radiation, and magnetic fields
  - -Calibration and alignment of large antennas
  - -Data package retrieval/replenishment
  - -Visual readout of engineering data
  - -Experiment operations
  - -Experiment monitoring

Future applications for providing the maneuvering capability are of three general types: aids for manual translation (handrails), devices mounted to the man which propel him through space (AMU, jet shoes), and platforms which carry the astronaut (LTV platform, Bendix platform, trolley devices).

Handrails

A study conducted for the Air Force on use of handrails in zero gravity (Sasaki, 1965) reported dual rail separation should be 16 to 24 inches. Parallel rails with less than 12 inches separation and single rails offered minimal body stability in terms of roll oscillations. In pressure-suited conditions, dual rail separation of 30 to 36 inches was judged definitely uncomfortable. These studies were conducted in parabolic flight using the AF A/P-225-2 full pressure suit at 3.5 PSIG. Rails were 1.25 inches in diameter, 84 inches long, and offered 2 inches hand clearance. The task required that the subject move along the rail and turn around at the end.

Body Mounted Devices

AMU - The Astronaut Maneuvering Unit (modular maneuvering unit) developed by LTV consists of a back-pack with propulsion/stabilization thrusters and individual controllers for attitude and translation control. The AMU included in the Gemini comprised the following subsystems: structures, propulsion, flight control, life support oxygen, power, alarm, and communications. The total weight of this unit was 168.3 pounds full and 137 pounds empty. Unit size was 35 inches high, 25 inches wide, and 17 inches deep. Total propulsion impulse was 3,000 to 3,500 pounds/seconds with a thrust of 2.3 pounds. Stabilization was provided by means of automatic attitude hold with rate command whereby a commanded attitude was held to $\pm 2.4^{\circ}$. Attitude rates of change were 18°/second for pitch and yaw and 27°/second for roll. Acceleration was .4 feet/second^2. Total life of the unit was one hour, and maximum range was 2000 feet. Rate gyros were used for sensing attitude and attitude changes. The flight control system provided for 3 degrees of rotational freedom and 2 degrees of translational freedom; no capability for lateral translation was included.

ASMU - The Automatic Stabilized Maneuvering Unit is being considered as a translation aid which will be evaluated in the M-509 experiment to be conducted in the orbital workshop. Since the unit will be employed within the OWS, no life support capability will be included. The ASMU, like the AMU, is back-mounted with side controllers for attitude and translation control. Unlike the AMU, it provides 6 degrees of freedom control and has the capability for lateral translation. The ASMU has the rate command attitude hold feature and will provide the capability for linear accelerations of .4 to .6 feet/second^2.

Advanced concepts - According to the North American study, the supporting research and technology needed to attain an operational maneuvering unit capability by the mid-1970's include the following:

- Hybrid propulsion system capable of hot gas modes of operation. Cold-exhaust type thrusters are required in the near vicinity of a spacecraft or another astronaut, while use of high impulse propellants with hot gas thrusters is more efficient for long excursions
- PLSS integrated into maneuvering unit. The advantage is in using a gaseous oxygen cold-gas supply which can also furnish life support oxygen.
- Attainment of a rapid response capability. Prolonged donning and checkout times (AMU checkout requires 25 minutes) of current concepts is a handicap.
- Hands-free control through voice or body dynamics.

Maneuvering unit operational requirements are summarized in Table 4-16.

EVA ASTRONAUT REORIENTATION RESEARCH

In early 1970, a series of experiments were conducted in zero gravity (C-135 aircraft at Wright Patterson Air Force Base) to verify the assumptions proposed by researchers (Kane, et al, 1968 and 1969) that man in a state of free fall can effect a change in his attitude orientation (i.e., roll, pitch, and yaw) through the application of appropriate

TABLE 4-16

SUMMARY OF
MANEUVERING UNIT OPERATIONAL REQUIREMENTS

PARAMETER	EXPERIMENT SUPPORT		EARLY RESCUE	OPERATIONAL REQUIREMENTS
	1971-74	Beyond 1975		
Duration	4 hrs.—not critical	4 hrs.—not critical	1.5 hrs.	1.5 to 4 hrs.
Range (feet)	300	3000	300	3000
Stabilization	All axes	All axes	All axes	All axes
Velocity—Maximum (fps)	< 1	< 1	< 1	6
Cargo transfer				
Mass (lbs)	80	300	300	300
Volume (ft^3)	3	8	8	8
Thruster	Cold gas	Hot gas	Cold gas	Hot or cold
Maneuvers				
Station keeping	X	X	X	X
Acceleration-deceleration	X	X	X	X
Worksite Dock	X	X	X	X
Small cargo	X	X	X	X
Large cargo		X		X
Docking	Rigid	Rigid	Rigid	Rigid
Storage (days)	28	60-90	28-90	28-90

maneuvers. The reorientation can be accomplished by the astronaut's moving various limbs of his body (involves controlled motions of arms or legs) and also by the use of body torso movements (e.g., animals--falling cats--and humans--gymnast, trapeze).

Astronaut transfer would be accomplished by the application of an impulse from a thruster (located at the center of gravity, contained on a back pack) which would be "fired" at the proper time and for the proper interval, combined with the appropriate maneuvers by the astronaut to reorient his thruster before refiring. Through a series of forward translations and reorientation, the astronaut could transfer with ease through a free space environment.

Providing the astronaut with self-reorientation capability can be attractive in its elimination of complex mechanical systems that are weighty and subject to failures or could at least be considered as a means of providing a "back-up" capability.

Crew and Cargo Transporters

Platforms for transporting men, and possibly cargo, fall into two general categories: those linked to the spacecraft structures (serpentuator, trolley) and those capable of independent operation (LTV maneuvering work platform and Bendix EVA work platform).

Serpentuator - In 1968 a study was performed for NASA to determine the man/systems feasibility of using the MSFC-developed serpentuator as an EVA aid for film retrieval on the ATM mission. In this mission, the primary requirement for an EVA aid would be to assist the astronaut in transferring himself and seven fresh film magazines from the airlock module egress hatch to each of the two ATM worksites--center work station and sun-end work station. After accomplishing this delivery task, the aid must assist the astronaut in returning himself and seven exposed film packages back to the hatch. The general requirements of the aid are that it possess the physical capability of performing the transfers, that adequate life support provisions are ensured, that the operation at no time degrades the safety of the astronaut, and that dynamics of motion are compatible with and controllable by a human operator (Bathurst and Mallory, 1968).

The Matrix study was an assessment of the degree to which these requirements were satisfied by the MSFC Serpentine Actuator or Serpentuator. This device consists of a series of connected, individually controlled and powered, articulated links with a roll-ring at the base and a payload cargo rack/ control station (CR/CS) at the tip. This device is depicted in Figure 4-7.

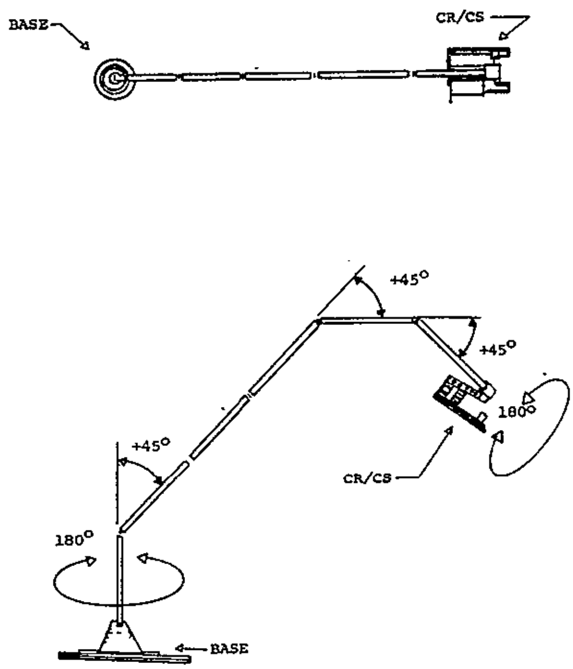


FIGURE 4-7 SERPENTUATOR DIAGRAM

The serpentuator configuration selected for evaluation consisted of eight links and was 40 feet long and 4.5 inches in diameter. Each link was assumed to have a maximum deflection of 45° in only one direction, and the base and CR/CS could be rotated ±180°. This configuration was selected to be compatible with stowage requirements at launch.

An investigation of forces generated by serpentuators of varying lengths reported that a 54-foot long, 10-link configuration of the same diameter as that selected for study on the ATM could exert 9.5 pounds of force at the tip. A force of this magnitude is capable of accelerating a 500-pound mass (the approximate mass of the astronaut, film magazines, and CR/CS) at a rate of .025 fps^2. If this acceleration is continued for a period of 20 seconds, the velocity of the payload will be approximately 4.2 fps.

In an effort to establish the geometric capability of the serpentuator, the surface of the geometric figure described by the tip when each joint is moved sequentially through its 45° and the base roll angle is held constant was plotted and is depicted in Figure 4-8. If this area is then rotated ±180° about the base, the solid which is generated represents the volume which may be reached by the tip when no obstructions are present. Comparing this envelope with that of the ATM cluster, it was obvious that both film retrieval work stations and the airlock hatch were well within the reach envelope of the Serpentuator. It was, therefore, assumed that the Serpentuator was conceptually capable of performing as an EVA translation aid for ATM.

In the life support area, the primary problem was umbilical management. A system for controlling the umbilical was proposed and is depicted in Figure 4-9.

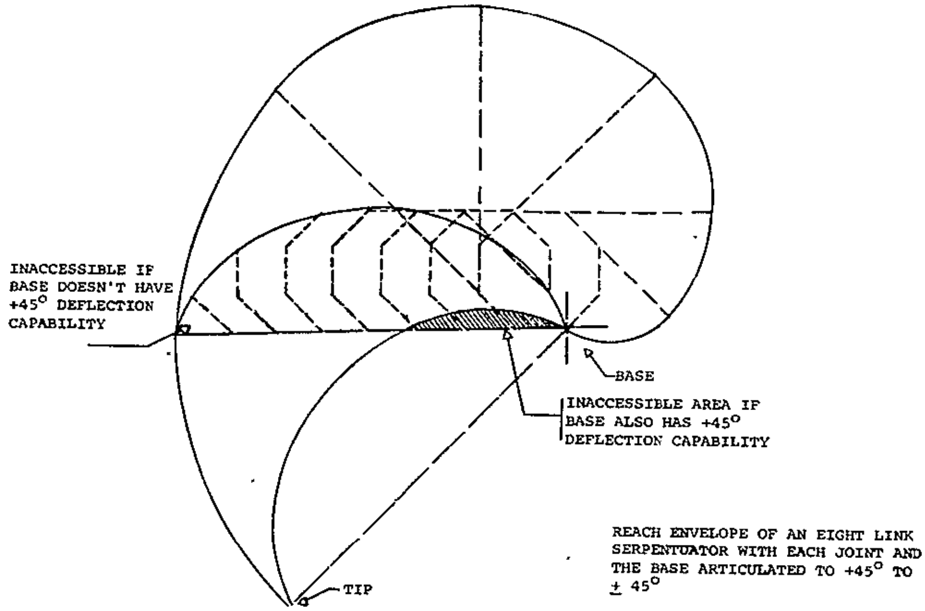


FIGURE 4-8 SERPENTUATOR TIP ACCESSIBILITY ENVELOPE

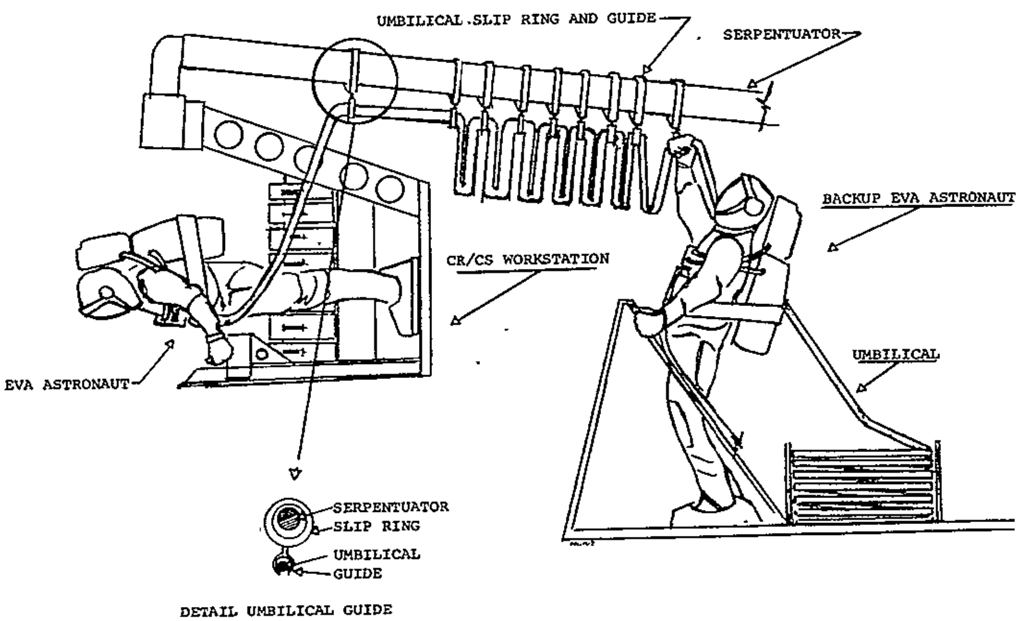


FIGURE 4-9 UMBILICAL SLIP RING GUIDE CONCEPT

In terms of astronaut safety, the primary contingencies expected with serpentuator operation were identified, and feasible solutions were developed to minimize the hazard. These contingencies and recommended solutions are presented in Table 4-17.

TABLE 4-17

POTENTIAL CONTINGENCIES AND PROPOSED SOLUTIONS

CONTINGENCY	SOLUTIONS
Incorrect positioning	Use of effective lighting Displays of each hinge angle Orient the astronaut to view along the path of travel Provide rate control
Inadvertant actuation	Provide master shutdown to deactivate power systems
Inadvertant deactivation	Provide handholds along serpentuator structures to enable manual transportation to the base
Primary life support failure	Provide an automatic "return to hatch" capability
Structural failure	Provide a means to remotely detach umbilical guides

Due to the complexity involved in manually selecting and positioning each of the eight (8) links to bring the CR/CS to the desired work station, an automatic programmed control of steering was recommended. Control of rates was to remain under astronaut control for safety reasons.

Based on this study, it was concluded that the Serpentuator was indeed feasible as an EVA aid for the ATM film retrieval operation. Man/systems design requirements reported in the study include

- 500-pound mass handling capability
- Acceptable ingress/egress capability
- Provide space for film magazine and cargo
- Maximum tip velocity of 4 fps $\pm$ 1 fps
- Provide smooth and continuous acceleration rates which minimize oscillation
- Permit umbilical or PLSS life support
- Provide quick-release umbilical restraint system which ensures that the umbilical is not damaged and does not interfere with operations
- Provide handholds along its length
- Provide adequate light--nominal and contingency modes
- Capability of delivering the astronaut back to the egress hatch within 6 minutes
- Provide an angle readout for correct and actual hinge or roll-ring deflection
- Provide dead man controller wherein rate is reduced to zero when in detent and rate is proportional to stick deflection when out of detent.
- Provide for overall systems shut-down
- Provide an automatic return-to-hatch capability

<u>Trolley device</u> - Another translation aid considered for the ATM mission was the trolley device developed at MSFC. This concept provided a support for the astronaut's feet and hands and a means of storing film magazines. The device was to be

mounted to a rail extending from the egress hatch to the work stations. As described in the report of the fourth ATM EVA working group meeting (24 October 1968), the design criteria for the device were as follows:

- The astronaut disembarks the device at the center end (formally the LM end) work station and accesses the prepared work station.
- The astronaut remains on the device for sun end film retrieval.
- Power required to operate the translator will be supplied by the astronaut.
- The device shall not impose a weight penalty of more than 100 pounds on the ATM.
- The torsional yield point of the rail cross-section is 850 in./lbs.

<u>Bendix Modular EVA Work Platform</u>

A work platform for translating the EVA astronaut in the local vicinity of the spacecraft is being developed by The Bendix Corporation (1969). This system consists of a maneuverable open-base for the astronaut and several modules for propellant and payload. The platform weighs 800 pounds unmanned, is capable of an incremental velocity of 300 fps, and can perform for a 4-hour period with an additional 4-hour capability for emergency.

The platform provides the astronaut with a relatively safe and non-taxing method of accomplishing many EVA tasks planned for advanced missions, including inspection, servicing, construction and assembly, repair, and cargo transfer. Design characteristics of the platform are presented in Table 4-18, and the configuration is depicted in Figure 4-10.

TABLE 4-18

BENDIX WORK PLATFORM DESCRIPTION

Propellant	Hydrazine
Plume temperature	1800° F
Thrusters	16 5-10 lb thrust
Closing velocity	15 - 20 fps
Operating ranges	1000 - 7000 feet
Acceleration	.5 fps^2

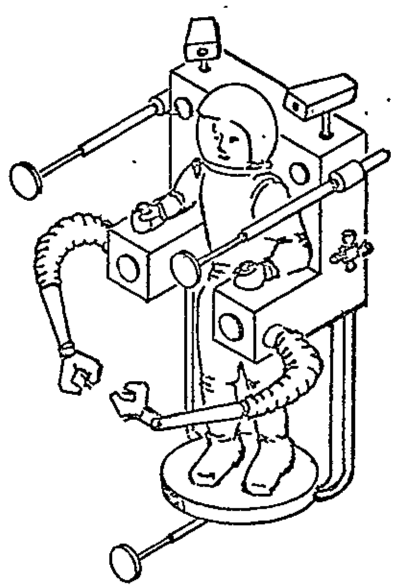


FIGURE 4-10 BENDIX WORK PLATFORM

Modules available to the platform include the long range rendezvous module, the extended propulsion capability module, and the payload module. The long range rendezvous module is required for missions requiring excursions in excess of 10,000 feet. The module provides radar parameters of azimuth, elevation, range, and range-rate for computer-controlled rendezvous. Radar maximum range is 250 miles. The extended propulsion capability module provides an increase in available delta velocity from 300 to 1085 fps. The delta velocity for the full-up platform is 975 fps. The payload module mounted on the floor of the platform provides storage for tools, spare parts, rescue equipment, repair kits, test equipment, and special work aids.

Stabilization is provided by automatic attitude control. All commands initiated by controller (attitude or translational) actuation result in full-on thruster firing. No proportional rate command is provided.

The platform is capable of serving as a portable worksite and can be fitted with manipulator arms to increase the reach and maintain and amplify forces provided by the astronaut. Worksite anchors are provided to connect the platform to structures. These consist of adhesive pads at the ends of three rods extending forward from the platform. The pads contain electrically heated epoxy adhesives and are left on the surface at undocking.

<u>LTV Maneuvering Work Platform (MWP)</u>

The MWP is similar to the Bendix platform in that it provides an open structure to support the suited astronaut and maneuver him independent of the prime vehicle (Figure 4-11). Design characteristics of this platform are presented in Table 4-19.

The MWP was deisgned for six basic missions which included equipment positioning, space maintenance, logistics, rescue, space assembly, and satellite operations. Master-slave manipulators are provided for stand-off operations, mass handling, grappling, and stabilization. Docking is achieved by use of the manipulators.

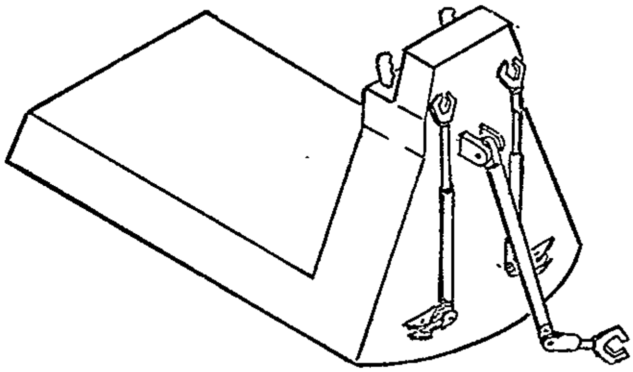


FIGURE 4-11 LTV MANEUVERING WORK PLATFORM (MWP)

TABLE 4-19

SUMMARY OF LTV
MANEUVERING WORK PLATFORM REQUIREMENTS AND CRITERIA

Overall length –	closed extended	84 inch 184 inch
Overall width		58.8 inch
Gross weight –	dry wet	1451 lbs. 1689 lbs.
Life support duration		8 hours
Metabolic rate –	average peak	1250 BTU/hr. 2150 BTU/hr.
Total heat load capability		21,129 BTU
Propellent		Hydrazine
Total Impulse		45,000 lb/sec.
Total delta velocity capability		860 fps
Stabilization & control deadboard		$\pm 2^{\circ}$
Accelerations –	roll pitch yaw forward trans. lateral trans. up/down trans.	$14.3^{\circ}/sec^2$ $14.7^{\circ}/sec^2$ $22.6^{\circ}/sec^2$ $.99\ fps^2$ $.495\ fps^2$ $.495\ fps^2$
Thrusters		24
Rotational rates		5 and 15° sec.
Radar Range		10.5 km
MWP Range		2 km (6562 ft.)
Velocity		10-15 fps nominal 40 fps emergency

TABLE 4-20 SUMMARY OF CURRENT EVA TRANSFER SYSTEMS

	RAILS	GTX HHMU	A M U	SERPENTUATOR	TROLLEY	PLATFORMS: BENDIX	PLATFORMS: L T V
PHYSICAL CHARACTERISTICS							
Power source	Man	Hydrazine	Hydrazine	Mechanical	Man	Hydrazine	Hydrazine
Weight (lbs)	Min.	3	168	200-300	100	800	1689
Oper. Life (hrs.)	4	.3	1	4	4	4	8
OPERATIONAL CHARACTERISTICS							
Range Ft.	Min.	50	2000	40	Min.	7000	6500
Velocity fps	2	6	1	4	1-2	15-20	10-15
Acceleration	Min.	.3	.4	.025	Unknown	.5	1
Energy Required	Max.	Mod.	Mod.	Min.	Mod.	Mod.	1250
Flexibility	Limited	Limited	Good	Limited	Limited	Good	Good
Astronaut Orientation	Good	Good	Good	Optimal	Poor	Good	Good
Worksite Interface	Good	Good	Fair	Problems	Problems	Excell.	Excell.
Rate Control	Min.	Problems	Yes	Excell.	Min.	No	Yes
Control Systems	Man	Hand Pointing	Controllers	Problems	Problems	Controllers	Controllers
SAFETY CONSIDERATIONS							
Effect of Failure							
Translation	Tether	Tether	Problems	Manual	Uncertain	Problems	Problems
Life Support	Return	Return	Return	Return	Catastrophic	Return	Return
Rescue Operations	Yes	No	Yes	Auto. Deploy	No	Yes	Yes
Automatic Return	No	No	No	Yes	No	No	No
Backup	Tether	Tether	None	Manual	None	None	None
PREPARATION REQUIREMENTS							
Checkout Time	Min.	Min.	Max.	Mod.	Min.	Mod.	Mod.
Deployment Time	Min.	Min.	Mod.	Mod.	Min.	Max.	Max.
CARGO TRANSFER CAPABILITY	No	No	Limited	Yes	Yes	Yes	Yes

Transfer System Summary

Table 4-20 presents a comparison of the various transfer concepts discussed in the preceding sections. In terms of astronaut operations and energy expenditures, the work platforms are most effective; in terms of safety, the serpentuator concept is superior. Consideration should be given to the distance to be travelled in the EVA and cargo transfer requirements as opposed to cost, weight, safety, and operability factors. For short traverses with cargo, a serpentuator is preferred. For longer excursions where an umbilical to the spacecraft is not feasible, a work platform is preferred. The HHMU should be considered primarily as a backup to the platform or for short traverses where cargo transfer is not required. The AMU is feasible if the life support system can be easily integrated with the propulsion system. Otherwise, the shortcomings of back pack devices limit their effectiveness for missions of the future.

The applicability of each transfer device for EVA functions described in Section 2.0 is presented in Table 4-21.

TABLE 4-21

APPLICABILITY OF CREW & CARGO TRANSFER DEVICES

FUNCTIONS \ DEVICES	RAILS	HHMU	AMU	SERP.	TROLLEY	PLATFORMS	
						BENDIX	LTV
Deploy	No	No	Yes	Yes	No	Yes	Yes
Remove/replace	No	No	Yes	Yes	No	Yes	Yes
Inspect	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cargo transfer	No	No	No	Yes	Yes	Yes	Yes
Maint. & repair	No	No	Yes	Yes	No	Yes	Yes
Operate	No	No	Yes	Yes	No	Yes	Yes
Satellite recovery	No	No	No	Yes	No	Yes	Yes
Rescue	No	No	Yes	Yes	No	Yes	Yes
Data Acquisition	No	No	Yes	Yes	No	Yes	Yes

4.5.2 Transport Systems

One of the primary considerations in the assessment of astronaut transfer aids is the capability of candidate systems to carry cargo. Cargo transfer concepts for operational, design, and research missions are discussed in the following sections.

OPERATIONAL CARGO TRANSFER

The only cargo transfer aid utilized in Gemini was velcro mounted on the ELSS chestpack to which packages and tools were affixed for transfer or temporary storage. This approach has limited effectiveness due to the small sizes of items to be carried and to problems with dislodging the items by contacting surfaces.

DESIGN MISSIONS

Due to the very recent decision to change the AAP workshop configuration from wet to dry, extensive modification of the ATM film transfer concept was required. Concepts being presently considered for astronaut/film transfer are described below (from Brown and Hayes, 1969).

Center Concept-A

Concept-A consists of a direct-line-of-sight "Endless" clothesline Film Transportation System (FTS) in conjunction with a dual rail astronaut translation system.

The FTS system is characterized by single film magazine transfer and is manually actuated from the Airlock Module (AM) external workstation. Temporary film magazine stowage receptacles are located in the AM hatch area. The FTS system may be automatically deployed, depending on the final ATM deployment system, or manually deployed by the astronauts.

The dual rail astronaut translation system consists of parallel handrails extending from the AM hatch workstation to the sun-end workstation. Sufficient handrails and handholds are provided to laterally translate from the dual rails into the center workstation. Portions of the dual rail system will be hard mounted during launch, and the remaining sections will be automatically deployed during ATM deployment or assembled by the astronauts during EVA.

Center Concept-B

Concept-B consists of an FTS identical to that of Concept-A with the exception of multiple film transfer capabilities. The film magazines (4) will be grouped and attached to the FTD as a unit. Temporary film magazine stowage facilities at the AM external workstation are eliminated. The astronaut translation system is identical to that of Concept-A.

Center Concept-C

The FTS in Concept-C consists of a flip-over device with the pivot point centrally located between the AM hatch workstation and the center workstation. The flip-over device is attached to a fixture extending from the ATM deployment structure. Actuation of the unit is from the AM external workstation through a mechanical linkage system. As in Concept-A, the FTS may be automatically deployed, depending on the ATM deployment system, or manually deployed by the astronauts. The FTS will adapt to transport both single and multiple film magazine units. The astronaut translation system is identical to that of Concept-A.

Center Concept-D

In Concept-D a Storable Tubular Extendible Member (STEM) device will serve as the film magazine transportation system. The STEM device is hard mounted near the AM external workstation with provisions to attach single film magazines. The STEM is electrically driven with a manual (crank) backup actuation mode. The STEM system is pre-aligned to deploy the film magazines to the astronaut at the center workstation. The astronaut translation system is identical of that of Concept-A.

RESEARCH MISSIONS

As indicated in Table 4-21, the cargo transfer function is feasible with the serpentuator, trolley, and both work platform concepts. The only one of these systems which could operate solely for cargo transfer (unmanned) is the serpentuator. The trolley relies on the astronaut for translation power, and the work platforms rely on man for control. A description of cargo transfer concepts is presented below.

Personnel Harness

Configuration of a body-mounted harness include a single package in front of the body or dual packages at the legs. The maximum dimensions of the single-pack concept are 15 inches by 15 inches by 30 inches, and the mass cannot exceed 100 pounds. Dual packages can be 12 inches by 12 inches by 30 inches in size and can reach a mass of 75 pounds each. While these devices present no unique technological problems, they must be designed so as not to restrict the astronaut's field of vision or body/limb mobility.

Serpentuator

The serpentuator configuration evaluated for the ATM was capable of transporting 500 pounds of astronaut and cargo. This device could also be used to transport cargo alone; however, a retrieval device would be required if an astronaut were not present at both ends of the traverse for loading and unloading.

Manned Platforms

The LTV Maneuvering Work Platform (MWP) has the capability to carry on-board and external payloads. Specific payloads and load limits are described in Table 4-22.

The Bendix platform provides for the inclusion of a payload module for transfer of tools, spare parts, rescue gear, repair kits, test equipment, and special workaids.

TABLE 4-22

SUMMARY OF
MANEUVERING WORK PLATFORM PAYLOADS AND LOADS

PAYLOAD	WEIGHT-POUNDS
On-board	
hand tools	48
maintenance equipment	40
diagnostic equipment	25
spares	100
External	
re-supply expendables	200
limited maneuvering	25,000
satellite capture	545

Tunnel Suits

While not specifically a cargo transfer device, the tunnel-suit concept does provide for limited astronaut translation about the surface of a spacecraft with the capability for transferring cargo. The system consists of a tunnel structure attached to the spacecraft at one end with a spacesuit torso assembly at the other. The system is maneuverable in that the astronaut can position himself at any workstation, and the assembly has a pass-through lock for transferring tools and packages in and out. The tunnel is positioned by flexing a joint at the airlock interface to position the tunnel within a cone of 30°. The tunnel is 30 inches in diameter and 20 feet in length (Richardson, 1969).

STEM

The Storable Tubular Extendable Member (STEM) presents a feasible method of transferring cargo. The equipment requires little storage volume and can be operated from a fixed base. One problem with the STEM is that it does not readily bend around structures and obstructions.

Rail

Single or dual guide rail systems are feasible and cargo transfer over the rails can be accomplished manually or in an automatic mode. A study by Garrett Corporation (Wortz et al, 1969) reported that single degree of freedom stabilization tracks are not sufficient for transferring cargo. The primary problem is astronaut control of the package.

Variable Flexibility Tether

The Variable Flexibility Tether system has been recommended as a cargo transfer device (Rader, 1968). This tether, described in detail in Section 4.3.1, was capable of resisting a movement of 75 feet/pounds. The stored volume of the unit is one cubic foot, and the weight is less than 10 pounds. It is operated by one man using one hand. It can be used to stabilize a 90th percentile astronaut, spinning at the rate of 10 rpm, in 10 seconds.

Lattice Boom

The Lattice Boom, or Astro Column, developed by Astro Research Corporation, Santa Barbara, California, consists of three longitudinal members intermittently connected by battens. Wires or cables diagonally connecting adjacent sets of battens provide the deployed structure with torsional stiffness. The column is packaged into small cylindrical volumes. With thin-walled aluminum tubing and tapes, the weight per foot of a 10-foot diameter lattice structure is .2 pounds. Changes in direction of the column are accomplished by extension of longeron elements, hence the device is not limited to a straight line of travel. The column can be deployed automatically of manually.

Clothesline

This device usually will be employed between docked vehicles and consists of a continuous cable over pulleys or rollers. Cargo attachment is via a frame or clamping device. The line provides 2-axis stabilization.

Requirements for future cargo transfer systems, as identified by North American, are summarized in Table 4-23.

4.6 SUMMARY OF MANUAL EVA TECHNOLOGY

Operational experience demonstrates that EVA is not only feasible as a total systems capability but, in certain instances, provides a level of flexibility and control not possible with unmanned operations. High astronaut workloads experienced in the conduct of nominal mission operations during Gemini, as well as the hazards associated with placing the astronaut in free space, point up the need for careful planning of EVA and consideration of astronaut support requirements. Workloads in nominal and contingency situations must be determined in high fidelity preflight simulation. Techniques for reducing astronaut effort during operations not directly related to the goal of the EVA (translation, site preparation, etc.) must be developed prior to the mission. Workspace layout, illumination, and EVA aid design requirements at a worksite must be analyzed and identified prior to flight. General guidelines for future missions include the following:

- Worksite technology
  - Provide foot restraints and handholds
  - Provide for rapid egress
  - Provide lighting--general area and directed rather than rely on natural light sources
  - Provide for umbilical management and life support backup

- Translation
  - Use unaided translation only for short, well-defined excursions
  - Within umbilical range, provide a carrier system which is linked to the spacecraft and can help support and manage the umbilical

For excursions not well-defined in terms of location and ranges greater than umbilical length capability, use work platforms rather than back packs (e.g., AMU's) due to cargo transfer capabilities

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SECTION V

REMOTE MANIPULATOR SYSTEMS

5.0 REMOTE MANIPULATOR SYSTEMS

The Remote Manipulator is a subclass of Teleoperators as defined by E. Johnson and W. Corliss in their AEC-NASA survey "Teleoperator Controls" (1967). These authors define a teleoperator as a general-purpose dextrous, man-machine system that augments man by projecting his manipulatory and pedipulatory capabilities across distance and through physical barriers into hostile environments. It is implicit in this definition that man is always in the control loop. The major classes of teleoperator are shown in Table 5-1.

TABLE 5-1

MAJOR CLASSES OF TELEOPERATORS

TYPE	CHARACTERISTICS
Manipulators	Mechanical analogs* of human arms and hands. Reproduce man's motion at a remote and/or hazardous location.
Prosthetic and Orthotic Devices	Mechanical analogs* of human arm and hand, attached directly to body.
Man Amplifier	Mechanical analog* of entire or large portion of human body; normally these are the exoskeletal type.
Walking Machines	Mechanical analog* of human legs controlled directly by operator (not preprogrammed).

*The analogs are not exact, and they have fewer degrees of freedom than those of a human being.

More specifically, the designator remote manipulator, as used in this report, refers to a collection of systems which are controlled by a human operator and perform a variety of tasks in a remote and/or hostile environment. The manipulator system permits man to extend his reach, to amplify his forces, if necessary, and thus increase his safety while reducing his fatigue.

The manipulator has been supplementing man's activities for over twenty years in the atomic energy installations, in undersea operations, and in many hazardous industrial applications. The majority of the early manipulators were developed by the Atomic Energy Commission (AEC) at the Argonne National Laboratory (ANL). Most of the state-of-the-art manipulators are based on principles developed by the ANL.

In more recent years manipulator systems solutions have been applied to many operational problems of inner-space in undersea applications. The undersea missions may be for scientific research, commercial operations, or military objectives. The inner-space, undersea operational problems are very similar to those posed by outer-space. Both present to man a hostile environment from which he must be protected, either by a form-fitting suit or by complete encapsulation such as a submersible or a spacecraft. Each require an appropriate means of locomotion and stabilization in a free-space condition. Keeping this in mind, the space systems designer can obtain a great deal of pertinent, transferable data from undersea technology.

5.1 CLASSIFICATION OF REMOTE MANIPULATOR SYSTEMS

At present, no standard classification scheme is universally accepted for manipulator mechanisms or systems. Some are classified in terms of degree of man involvement at the man-machine interface (Baker, 1962). Five classes have been defined:

- Automatic
- Semi-Automatic
- Direct Control

- Semi-Remote Control
- Remote Control

Others are classified in terms of their energy input and the relationship of control to the manipulator actuator. These are grouped into three general categories (Blackmer, 1968):

- Manual Master-Slave (M/S)
- Electric Panel-Control (PC)
- Electric Master-Slave (M/S)

Still another method of classifying manipulators is to compare their functions to those of the human arms and discuss them in terms of the actions of the joints (rotary or pinned) and the input-output relationship of the system. Most existing non-space related manipulators in use today are classified in this manner and are further broken into two general groups--Bilateral and Unilateral.

All of the aforementioned classification schemes are based on parameters (e.g., type of energy inputs, control functions and joint design, etc.). These schemes are appropriate and sufficient for discussing Earth-based systems in which the term "manipulator" is used to describe mechanistic components used to manipulate objects in some remote or hostile environment. But it is felt that these classifications are not broad enough for use in discussing the functions which are required and which should be considered by future mission planners and designers in their attempt to accomplish a specific space mission. Since the actual manipulator mechanism is only a part of the total system, the classification categories that will be used in this document will be based on the manned/unmanned mission requirements and will determine the relationship between the man/manipulator and the primary space vehicle or platform. The subclassifications will be as follows:

- Prime Vehicle-Manned (PV-M)
- Auxiliary Vehicle-Manned (AV-M)

- Auxiliary Vehicle-Unmanned (AV-UM)

- Auxiliary Vehicle-Unmanned (AV-UM)
  - PV-M controlled
  - Ground Controlled

These classifications will be amplified later in the section.

Because the existing Earth-based manipulator technology is, and will continue to be, the source of ideas for advanced space manipulator systems, it is necessary to be familiar with these existing systems.

5.1.1 Existing Non-Space Manipulators

Before the descriptions of the existing manipulator can be fully appreciated, it is necessary to have an understanding of the terms of the technology and to consider the characteristics of the objects to be manipulated.

An ideal manipulator must reproduce in a remote location all of the motions that a human arm and hand are capable of producing. Such a system would feedback all of the information that is normally needed for a person to perform an operation. Since any object that is to be manipulated has the capability of six independent degrees of freedom (three translational and three rotational), the ideal manipulator must be capable of grasping an object and applying to it controlling forces, torques, and motions. Therefore, the system would require a minimum of seven independent motions--three for translational movements, three for rotational movements, and one for grasping. There are many existing systems with seven or more basic degrees of freedom, but few have the capability of providing all of the feedback the man normally uses in performing operations directly (e.g., audio, visual, force and position, and tactile). Many systems can feedback all or any combination of audio, visual, and force and position; but at present there is no practical way of feeding back the tactile information.

As mentioned previously, most of the existing manipulators are broken into two general groups--Bilateral and Unilateral. Simply defined, a Bilateral manipulator is reversible (in terms of force and motion being reflected from the master to the slave or vice versa) and the unilateral is not. Three simplified manipulator concepts which enable a human operator to control an output joint at some distance from input are depicted in Figure 5-1 (Interian-Kugath, 1969).

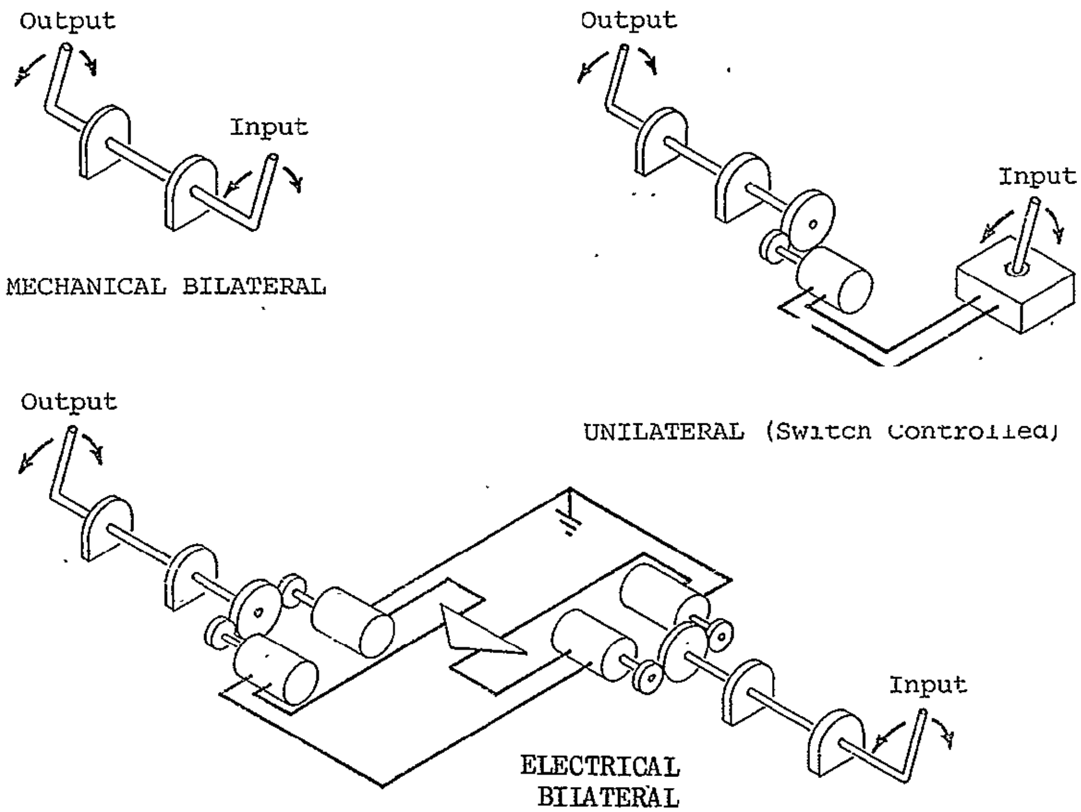

FIGURE 5-1 SIMPLIFIED MANIPULATOR JOINT DIAGRAMS

DESCRIPTION OF BILATERAL MANIPULATORS

Bilateral manipulators are reversible. This means that a force or motion applied at the input (master handle) will produce, through the control system and mechanisms of the manipulator, a force or motion at the output (slave "hands"). Similarly, if a force or motion is applied at the output, it will produce a force or motion at the input (LTV, 1966 and ANC, 1967).

Bilateral manipulators are further classified into two groups as shown in Figure 5-2. Most bilateral manipulators are the master-slave type. There are also a few other types, such as the ball-joint manipulator, which have force and motion feedback but lack other desirable features found in master-slave manipulators.

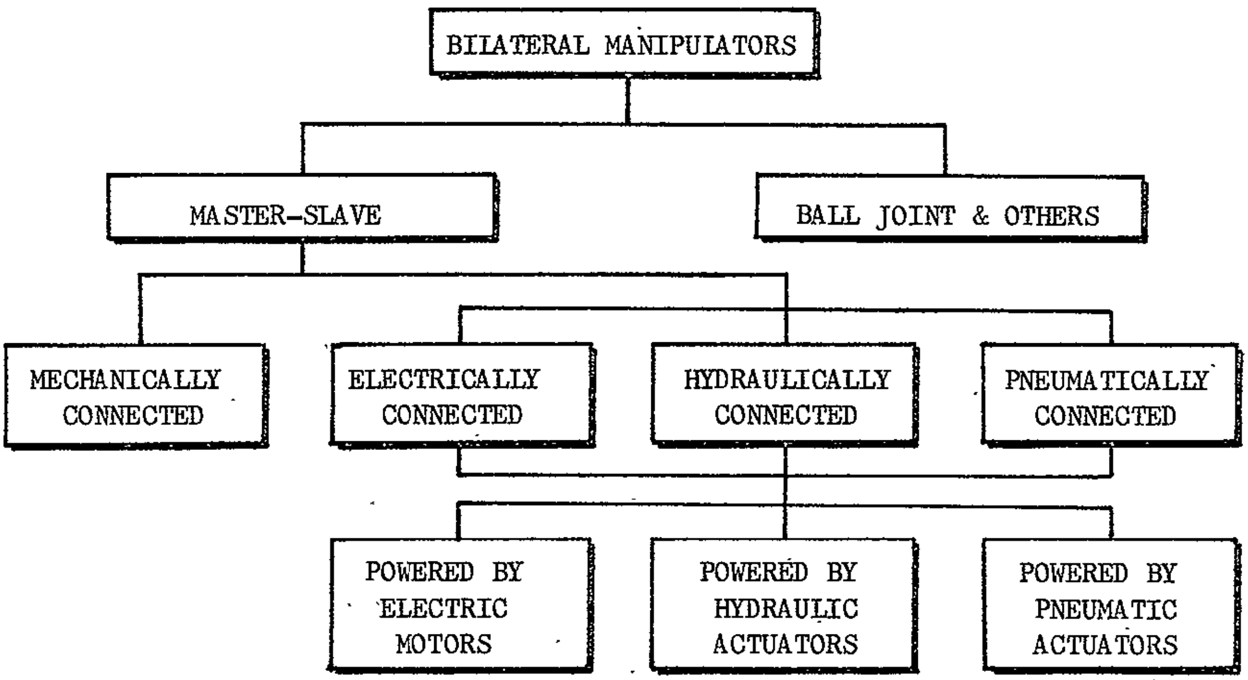

FIGURE 5-2 CLASSIFICATION OF BILATERAL MANIPULATORS

Master-Slave Manipulators

A master-slave manipulator has a remotely located mechanical "slave" arm which is controlled by an operator using a similar "master" arm. The master arm and the slave arm each have at least the seven basic independent motions, but they can have more. Each motion of the master is connected to the corresponding motion of the slave by highly reversible mechanical or electronechanical devices so that positions, forces, and torques are repeated proportionally from master to slave and from slave to master. All seven or more motions can be controlled simultaneously, and the operation is quite natural--that is, somewhat as if the operator were doing the work directly with his arms and hands.

The most widely used mechanically connected master-slave manipulator is the ANL Model-8, shown in Figure 5-3. It was developed by Argonne National Laboratory and is produced commercially by Central Research Laboratory (CRL) and American Machine and Foundry (AMF).

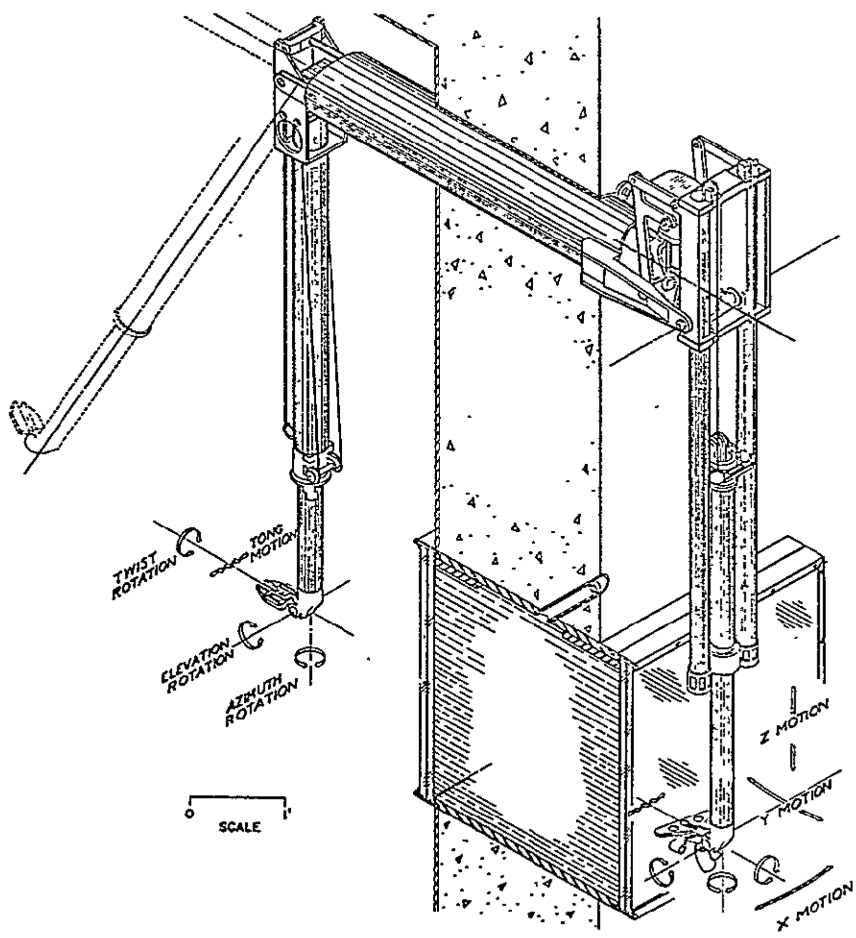

FIGURE 5-3 THE ANL MODEL M8
MECHANICAL MASTER-SLAVE MANIPULATOR

In the ANL Model M-8, efficient mechanical linkages connect the seven motions of the master arm to the corresponding motions of the slave arm in a 1:1 position and force relationship. Although only one manipulator arm is shown in the figure, it is desirable and common practice to use them in pairs. Because there are no dextrous multiple finger movements as in the human hand, it is often necessary to pick up an object with one manipulator and use the other to reorient it in the "hand" of the first.

Figure 5-4 is a schematic of an electrically connected master-slave manipulator. Special force reflecting servos are used to supply the near equivalent of efficient, bilateral mechanical linkages.

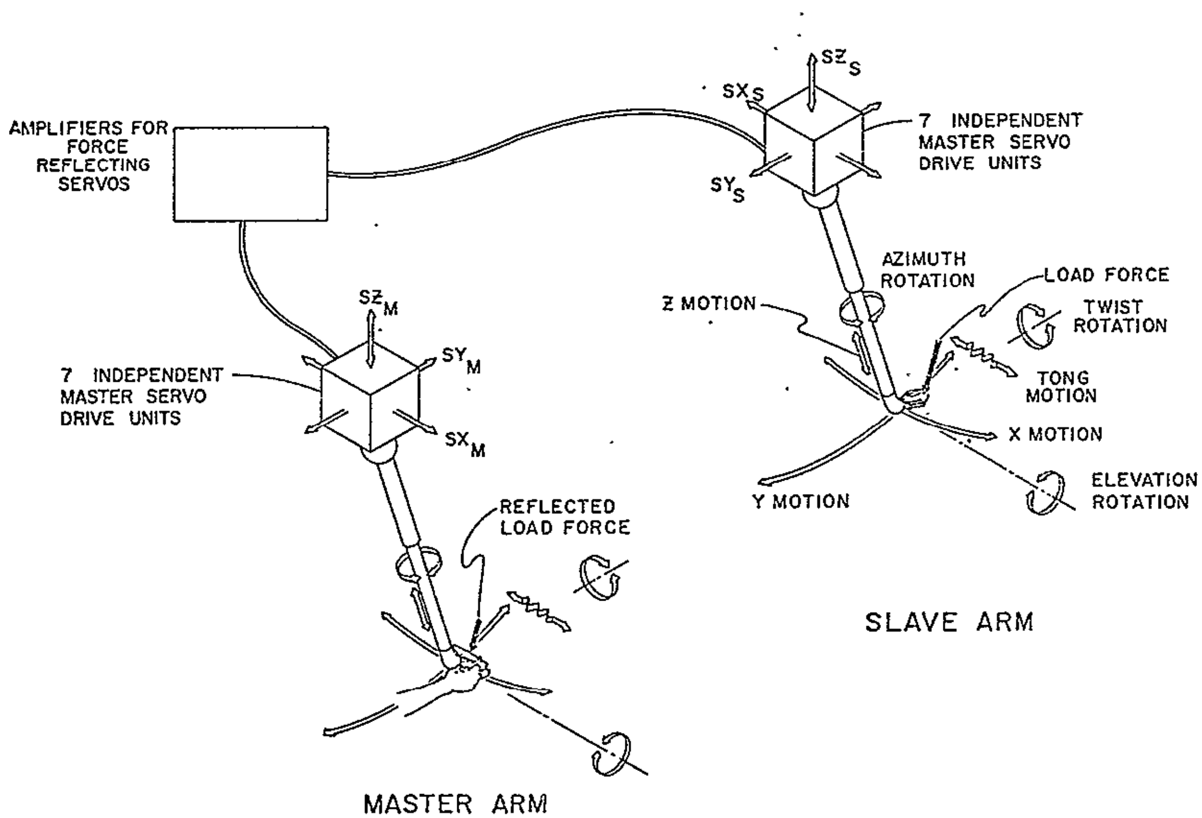

FIGURE 5-4 ELEMENTARY DIAGRAM OF AN ELECTRICAL MASTER-SLAVE MANIPULATOR

Because the master and slave arms are connected with an electric cable, they can be supported on mobile devices and moved throughout large volumes. The master and slave arms move in a 1:1 motion correspondence. Force multiplication ratios between the slave and master of 1:1, 2:1, and 5:1 are incorporated; using a switch, the operator can select the ratio wanted. In electrically connected manipulators, different motion-multiplication ratios could also be provided by circuit switching techniques. With force multiplication an operator can, for example, manipulate force of 50 pounds at the slave while exerting only 10 pounds at the master.

All master-slave manipulators, both the electrically connected and the mechanically connected, have the following set of characteristics:

- Slave arm and master arm have at least the seven basic motions.
- Motions, forces, and torques are reproduced proportionally from master to slave.
- Motions, forces, and torques are fed back proportionally from slave to master.
- Master handle suitably couples seven basic motions to the operator's hand.
- Slave "hand" can quickly couple six basic motions of slave to an object.
- Operation is quite natural.
- All basic motions are controlled simultaneously with one hand.

These characteristics can be used to define a master-slave manipulator. No other type of manipulator has all of them.

Ball-Joint and Other Bilateral Manipulators

The manipulators discussed in this section, although bilateral, are not master-slave. All have one or more motions reversed (i.e., an upward motion at the master produces a downward motion at the slave). Some have less than the seven basic motions or have a motion and force ratio between the handle and tongs which varies with the position of the manipulator. These characteristics make them more difficult to operate than master-slave manipulators.

A simple ball-joint manipulator having five motions is illustrated in Figure 5-5. Two of the motions are obtained by pivoting the ball in its socket; another motion is produced by sliding the manipulator arm in the ball. The fourth motion is rotation about the longitudinal axis, and the fifth is the long squeeze or closing motion. This particular manipulator does not meet the requirement of having seven independent motions; however, others having this same general construction have been designed which do include all seven degrees of freedom.

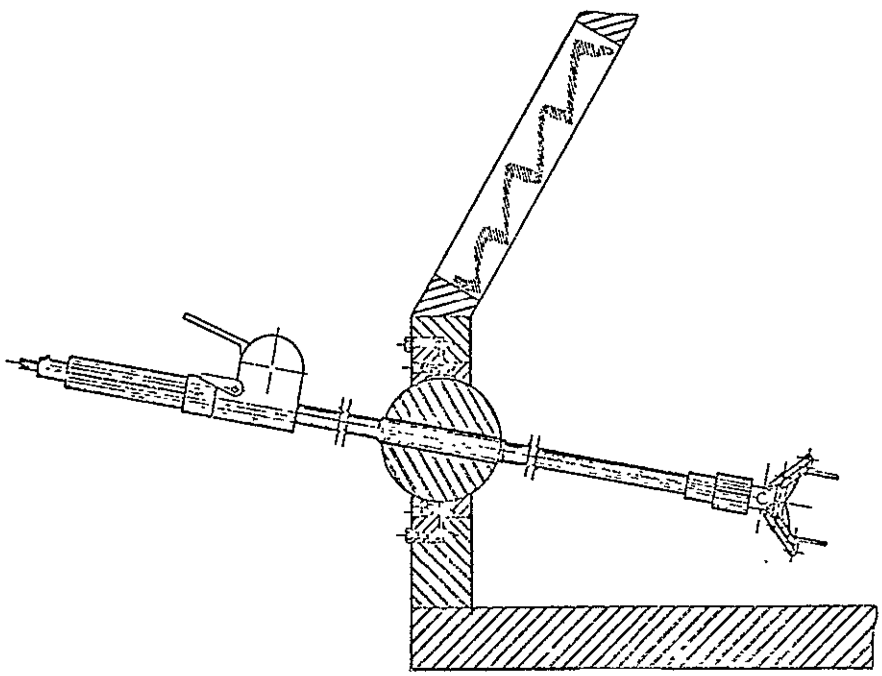

FIGURE 5-5 STANDARD BALL-JOINT MANIPULATOR

DESCRIPTION OF UNILATERAL MANIPULATORS

As noted previously, unilateral manipulators are not reversible; there is no force or motion feedback from the output to the input.

A unilateral manipulator consists of a mechanical working arm having several independent, motor driven motions which are controlled in speed and direction by proportional controllers. It is extremely difficult, and often impossible, to control the forces exerted by a unilateral manipulator. While most have some means for limiting the maximum forces applied, there is no force feedback and, therefore, the forces available cannot be well controlled under the maximum values. The unilateral manipulator's lack of force and motion feedback makes it basically unsuitable for machinery repair, maintenance, or assembly. It cannot comply efficiently to restrained paths, it has very little dexterity, it is time-consuming in performing even simple tasks, and it can easily damage equipment being handled.

Figure 5-6 shows the further breakdown of this manipulator classification.

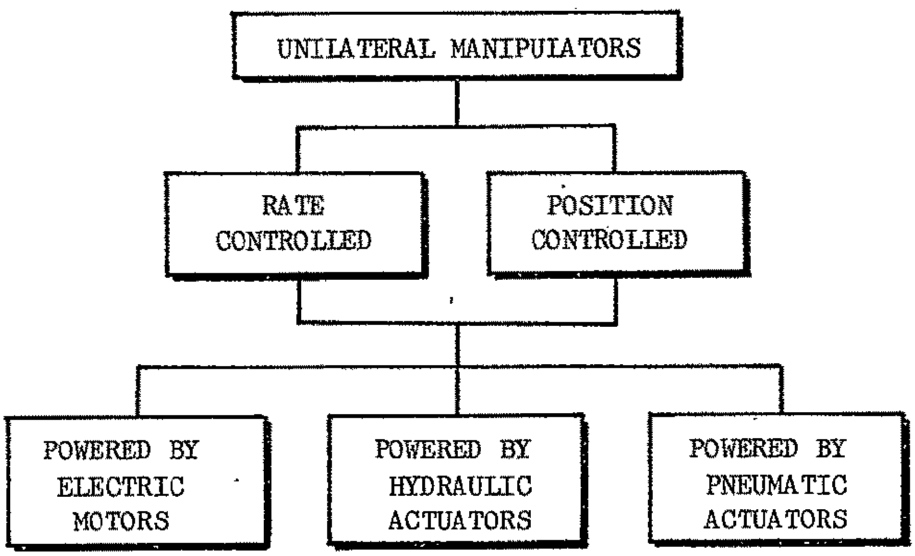

FIGURE 5-6 UNILATERAL MANIPULATOR CLASSIFICATION

The unilateral manipulator may be mounted on a bridge and rail system (Figure 5-7), floor support system, or by various other means; unilateral robots have been built. The console containing the controls is usually portable so that it can be located for the convenience of the operator. Groups of controls are sometimes coupled to one control handle.

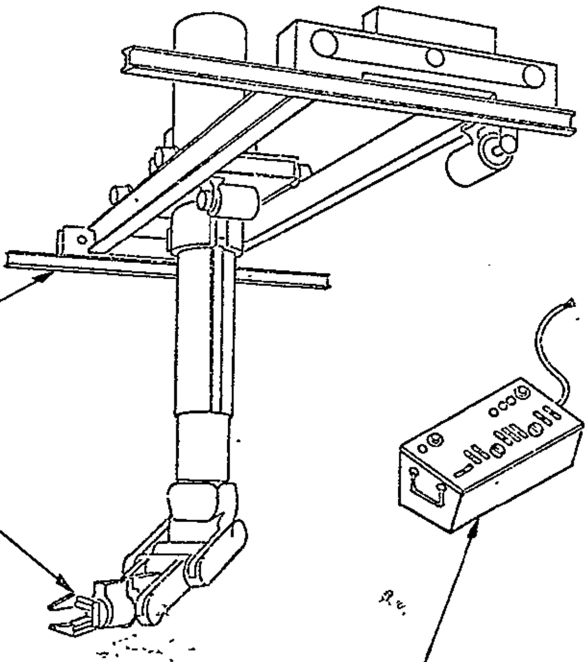

FIGURE 5-7 TYPICAL UNILATERAL MANIPULATOR AND SUPPORT SYSTEM

SUMMARY OF EXISTING MANIPULATOR SYSTEMS

Table 5-2 describes the characteristics of manipulators, as obtained by R. H. Blackmen, et al, in a literature study (Remote Manipulators and Mass Transfer Study--this was updated with later information). Definitions of the table headings are:

- Class - Unilateral, no force feedback; Bilateral, force and position feedback

- Slave power - basic power source used to operate the slave actuators
- Terminal device freedom - degrees of freedom at the terminal device
- Number of joints - total number of joints in one arm including tong motion
- Specifications - the published load and dimensional limits for one slave arm

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TABLE 5.2 MANIPULATORS - A SURVEY OF THE LITERATURE

MANIPULATOR	CLASS		SLAVE POWER			TYPICAL INSTALLATION	SPECIFICATIONS								STATUS					REMARKS
	Unilateral	Bilateral	Manual	Electric	Electrohydraulic		Six Degrees	Less Than Six Degrees	Number of Joints	Reach (Inches)	Load (Pounds)	Tong Opening (Inches)	Gripping Force (Pounds)	Slave (One Arm) Weight (Pounds)	Developed After 1962	Prototype	Catalog	Operational	Inactive	
ACF Industries, Inc. and Underwater Research Corporation	x				x	TRIESTE II		x	6	120	500	10		2390						
American Machine and Foundry Company																				
Model 8 Standard Duty		x	x	a		Hot Lab/Hazardous Location	x		7	97	10	3.2	20	500[b]			x			a) Y indexing; X optional
Model 8 Standard Duty (Extended Reach)		x	x	a		Hot Lab/Hazardous Location	x		7	136	10	3.2	20	580[b]			x			a) Y indexing; X and Z optional
Heavy Duty		x	x	a		Hot Lab/Hazardous Location	x		7	97	40	3.2	60	500[b]			x			a) Y indexing; X optional
Heavy Duty (Extended Reach)		x	x	a		Hot Lab/Hazardous Location	x		7	136	40	3.2	60	580[b]			x			a) Y indexing; X and Z optional
Light Duty (Extended Reach)		x	x	a		Hot Lab/Hazardous Location	x		7	73	7	3.2	10	175[b]			x			a) Y indexing
MiniManipulator		x	x	a		Hot Lab/Hazardous Location	x		7	36	5	3.0	10	16[b]			x			b) Master and slave
Argonne National Laboratory																				
Model 1		x	x			Hot Laboratory	x													
Model 4		x	x			Hot Laboratory	x		7		5		10						x	
M7		x	x			Hot Laboratory	x		7		5		10	30				x		
M8		x	x	a		Hot Laboratory	x		7		20		20					x		a) XYZ indexing
E1		x		AC		Hot Laboratory	x		7											
E2		x		AC		Hot Laboratory	x		7		8			200						
E3		x		AC[b]		Hot Laboratory	x		7		50	3.0	58	550				x		a) Z indexing
E4A		x		AC		Hot Laboratory	x		7		50	3.0	75	375	x	x				
Casteau (France)	x				x	DIVING SAUCER SP-300		x		40	25	a		35						a) Clamshell
Central Research Laboratory Inc.																				
Model 7		x	x			Hot Lab-Explosive Location[a]	x		7	50	10	3.2	10	60			x			a) Over-wall type
Model 8		x	x	a		Hot Lab-Explosive Location	x		7	103	20	3.2	20	225			x			a) Y indexing; X optional
Model A		x	x	a		Hot Lab-Explosive Location[b]	x		7	98	20	3.2	20	550			x			a) Y indexing; X optional b) Gastight
Model B		x[a]	x			Hot Lab-Canal		x	4		100	3.2	100	70			x			a) In wrist and tong motions
Model D		x	x	a		Hot Lab-Explosive Location	x		7	103	100	3.2	100	400			x			a) Y indexing; X optional
Model E		x	x	a		Hot Lab-Explosive Location	x		7	138	20	3.2	20	425			x			a) YZ indexing; X optional
Model F		x	x	a		Hot Lab-Explosive Location	x		7	135	100	3.2	100	600			x			a) YZ indexing; X optional
Model G		x	x	a		Hot Lab-Explosive Location	x		7	65	10	3.2	10	150			x			a) Y indexing; X optional
Model H		x	x	a		Hot Lab-Explosive Location	x		7	50	10	3.2	10	110	x		x			a) Y indexing;
Model J		x	x	a		Hot Lab-Explosive Location[b]	x		7	135	20	3.2	20	650	x		x			a) YZ indexing; X optional, b) Gastight
Comitato Nazionale per L'Energia Nuclear (Italy)																				
Mascot - 1		x		AC	x[b]	Hot Lab-Explosive Location	x		7	38	50	3.0		1700[a]	x	x				a) Two arms and mobile base b) Lifting column and trolley
General Dynamics Corporation																				
Model 3BH	x				x	Submersibles		x	6	48.6	85	6.0	500	465	x		x			
Model 4BH	x				x	Submersibles		x	6	57.4	85	6.0	500	505	x		x			
Model 5BH	x				x	Submersibles		x	6	63.5	85	6.0	500	540	x		x			
Model 6BH	x				x	Submersibles		x	7	63	85	6.0	500	540	x		x			
Model 7BH	x				x	Submersibles		x	8	69.6	85	6.0	500	575	x		x			
Model 8BH	x				x	Submersibles		x	7	74.2	85	6.0	500	580	x		x			
Prototype	x				x	Submersibles		x	6	60	100	3.2	500	150	x	x				
General Electric Company																				
Model AMU	x				x	ALUMINAUT		x	6	109	200	6.0	250	1705[a]	x			x		a) Two arms
Hanford		x	x			Hot Laboratory	x		8	48	20	4.0	20	100					x	
Handyman		x			x	Hot Laboratory	x		10[a]	60	100	5.0	150	550[b]					x	a) Special hand motions b) Two arms
Model III-H	x			x		Hot Laboratory		x	6	105[a]	600	5.4	1500				x			a) Extended
"O" Man	x			x		Hot Laboratory	x		9	72	500	6.0	500	1000				x		
Model III-H on Nerva Boom						Hot Laboratory			10	483	600	5.4	1500						x	a) Uses Model III-H manipulator
G-man II		x	x			Hot Laboratory	x		8	79	17	3.5	20	530					x	
General Mills, Inc.[a]																				a) General Mills Manipulator Business Sold to PAR
Model 100	x			x		Hot Laboratory		x	4	18	40	4.0	50	400						
Model 150 (Modified)[a]	x			DC		TRIESTE		x	6	39	50	2.0		110		x				a) Modified by Litton Industries
Model 150	x			DC		ALVIN		x	6	63.5	50	4.0	100	450		x				
Model 300	x			x		Hot Laboratory			5	37	65	5.0	150	175						
Model 500[a]	x			DC	x[b]	Remote Underwater Manipulator		x	5	180[b]	500	6.0				x				a) Modified b) Hydraulic boom
Model 500	x			x	x[a]	Hot Laboratory		x	5	134[a]	280	7.5	280	750						a) Hydraulic boom
Model 550	x			x		Hot Laboratory		x	7	132.5		5.0	200							
Model 700	x					Hot Laboratory		x	5	114		3.5	1500							
General Motors Defense Research Labs				x		Deep Ocean Work Boat (DOWB)	x			49	120	4	120		x					80 in. pounds of torque
Grumman Aircraft Engineering Co.						OSV-1 Submersible			8	200 92[a]	300 1120[a]					x				a) At maximum position
International Underwater Research Corporation	x				x	RECOVERER I		x	6	120	500	8.0								
LIP Company (France)				x		Hot Laboratory		x	4		4	4.0	10							
Lockheed Missile & Space Company						DSRV			7	110		4	2000							
					x	Deep Quest			7	107	500	8	500							
Naval Electronics Laboratory	x				x	TRIESTE II		x	4	180	500	18[a]		1330					x	a) Clamshell
North American Aviation, Inc.																				
Model 2	x				x	Submersibles	x		8	72	50	4.0[a]	2000[a]	240						a) Hook terminal device
Nuclear Equipment Limited (England)																				
Model 8						Hot Laboratory					20									
Model 9						Hot Laboratory					96									
Programmed and Remote Systems Corporation																				
Model 1000	x[a]			AC		Hot Laboratory		x	4	27.2	80	5.0	200	90		x				
Model 2000	x[a]			AC		Hot Laboratory		x	6[b]	37.5	150	5.0	200	150		x				a) Motion and position correspondence controller available. Wrist rotation and grip on a rate basis.
Model 3000	x[a]			AC		Hot Laboratory		x	7[b,c]		150	5.0	200	170		x				
Model 3500	x[a]			AC		Hot Laboratory		x	6[c]	39	100	4.0	150	110		x				
Model 3500 Underwater	x[a]			DC		Submersibles		x	6	49	50	4.0	100	185	x	x				b) Wrist pivot optional
Model 6000	x[a]			AC		Hot Laboratory		x	6	56	400	8.0	500	270		x				c) Wrist extension
Tokyo Shibaura Electric (Japan)																				
Type TP-1		x	x			Hot Laboratory			5			4.9	155							
Westinghouse Electric Corporation	x				x	DEEP STAR		x		40	25	a		62	x					a) Three-lobes clamshell

FOLDOUT FRAME

FOLDOUT FRAME

5.1.2 Classification of Space Manipulator Systems

It can be seen in Section 5.1.1 that the present methods of classifying Earth-bound manipulators are not broad enough to be used for the space manipulator system. In most cases the existing use of the term "manipulator" connotes a mechanism composed of an input control, a series of connecting linkages (either mechanical or electrical), and an output actuator. In this section the manipulator concept will be expanded to a concept in which the manipulator mechanism (actuator) is only a subsystem in the total Manipulator System.

A Space Manipulator System is a system which is capable of performing in a zero-gravity free-space environment. The system must be capable of completing the missions and performing the Extravehicular Activity (EVA) functions as described in Section 2.0 (e.g., cargo transfer, assembly/disassembly, satellite capture, etc.).

The system includes the following sub-systems:

- Translation
- Stabilization
- Actuation
- Control

The subsystems are integrated into a vehicle or a platform capable of performing the manipulation.

The Space Manipulator Systems are further classified into two subgroups as shown in Figure 5-8.

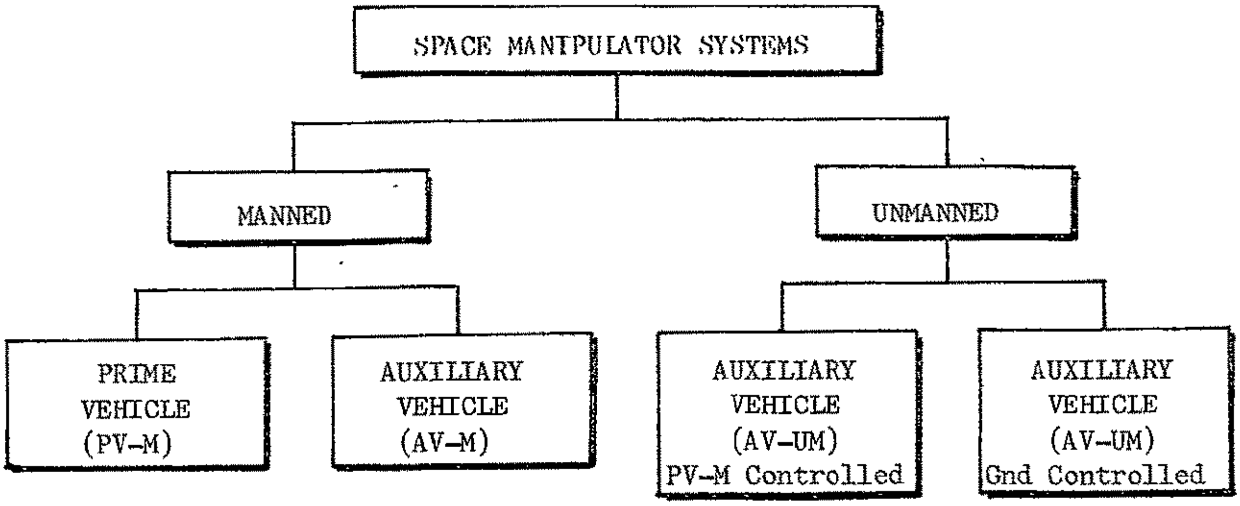


FIGURE 5-8 CLASSIFICATIONS OF SPACE MANIPULATOR SYSTEMS

MANNED SPACE MANIPULATOR SYSTEMS

As this subclass title implies, man is an active part of the system. He either controls or monitors/directs the manipulatory subsystems. The manipulator actuator is attached to the vehicle which is confining the astronaut and is providing him with the transportation, stabilization, and support functions. Two examples of this subclass include manipulators associated with the prime vehicle and those connected to an auxiliary vehicle.

Prime Vehicle-Manned (PV-M)

This is a system with the following characteristics:

- Remote manipulator mounted to prime vehicle structure (outside of spacecraft)
- Operating astronaut internal to prime vehicle (IVA)
- No additional life-support system required since that provided by the prime vehicle is sufficient

- May have direct visual access to worksite or employ a sensor (video)

- Manipulator mechanism not anthropometric or anthropomorphic (dimension or shape of human form)

- Coarse transportation and stabilization provided by prime vehicle (fine movement provided by manipulator mechanism)

- Transportation range limited to that of prime vehicle propulsion system and manipulator arm length

Figure 5-9 illustrates a simplified sketch of a prime vehicle-manned system.

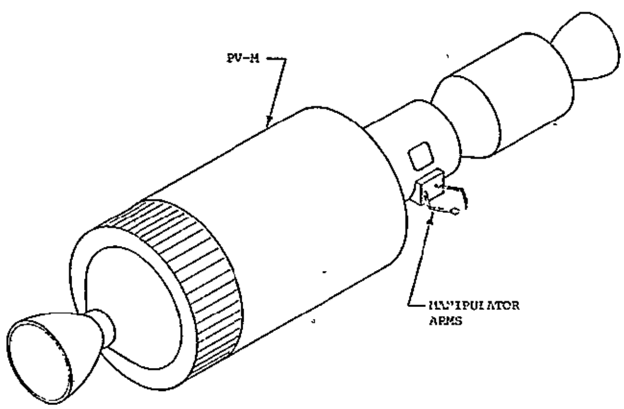


FIGURE 5-9 POSSIBLE PRIME VEHICLE-MANNED SYSTEM

Auxiliary Vehicle-Manned (AV-M)

This system has the following characteristics:

- Prime vehicle used as support base (tender)

- Range from prime vehicle dependent upon AV-M propulsion and life-support capability.

- Manipulator mounted to secondary craft or space platform
- Operating astronaut internal to auxiliary craft
- Astronaut not dependent upon prime vehicle for life support (except for re-supply)
- Direct visual access to worksite
- Manipulator mechanisms likely to be anthropometric and anthropomorphic.
- Movement around worksite unlimited

UNMANNED SPACE MANIPULATOR SYSTEMS

In this subclass man is remote from the manipulator system. The system is auxiliary to the prime vehicle. The system controller is not extravehicular. Control from a ground base station is not within the scope of this report; therefore, the only remote manipulator systems (AV-UM) to be discussed will be those controlled or monitored/directed by an astronaut located in a prime vehicle. The only category to be considered in this subclass is the auxiliary vehicle-unmanned (AV-UM).

Some primary characteristics of this system are:

- Man remote from manipulator and contained in prime vehicle
- System dependent upon prime vehicle as support base (tender) for consumables
- Range from prime vehicle dependent upon AV-UM consumables storage

The system/worksite interface should be similar to man/worksite interface to minimize operator control problems. This can be accomplished by:

- keeping the force, reach, and responses of a typical man;

- utilizing a video link between slave (worksite) and master (prime vehicle). The camera/manipulator arms relationship should correspond to that of the human eyes/arms; and

- having system similar to human in anthropometric and anthropomorphic sense.

5.2 CHARACTERISTICS DESIRABLE IN SPACE MANIPULATOR SYSTEMS

Both the General Electric Company and LTV Aerospace Corporation have determined that there are certain characteristics that would be desirable in any space manipulator system. Their conclusions were made from an examination of experiences with manipulators used in nuclear laboratories and from their studies in developing systems that can perform the necessary operations in a space environment (LTV, 1966 and Blackmer, 1968).

Some of the desired characteristics are:

- The manipulators should be bilateral (master-slave). These permit a natural mode of operation, enable an operator to feel and control the forces involved, and provide an efficient means for accommodating restrained paths in equipment.

- The slave arms should be capable of working throughout relatively large volumes--at least 100 cubic feet per pair. This would allow many tasks to be completed with a minimum of movement of the vehicle.

- The slave arms should be able to approach the work from different directions without relocating the vehicle. They should also be capable of working in areas where the access is limited by other equipment.

- The slave "hands" should be capable of grasping a wide range of sizes and shapes of objects. It should also be possible to use tools efficiently by having them fit into the "hand" or by removing the "hand" entirely and connecting the tools directly to the wrist stub.

- The docking slaves should have interchangeable, special attachments for docking to differing satellite structures.

- The force capability should be adequate to operate astronaut "hand" tools but should not exceed that of an extravehicular astronaut. This force capability is estimated to be 15 pounds.

- Response should be high enough to make the operator the limiting factor in determining task speed. This means no-load accelerations at the hands of about one "g" and no-load velocities of 30 inches per second for bilateral control.

- Anthropometric relationship between the "hands" and the TV "eye" should be provided to utilize the operator's natural and learned responses.

- Tools and procedures will be provided whenever capabilities must be augmented.

- The motions of the master should remain "in phase" with the motions at the slave. That is, a horizontal input by the astronaut should always produce a nearly horizontal output at the slave.

- The manipulator should have low friction, low backlash, and low inertia as seen at the master handle and slave "hands".

- The manipulator should have a high natural frequency (several cps) and/or considerable damping to prevent undesirable oscillations when handling masses.

- The manipulators should be highly reliable and require little maintenance.

- The manipulators should be configured so that the arms themselves restrict the operator's view as little as possible.

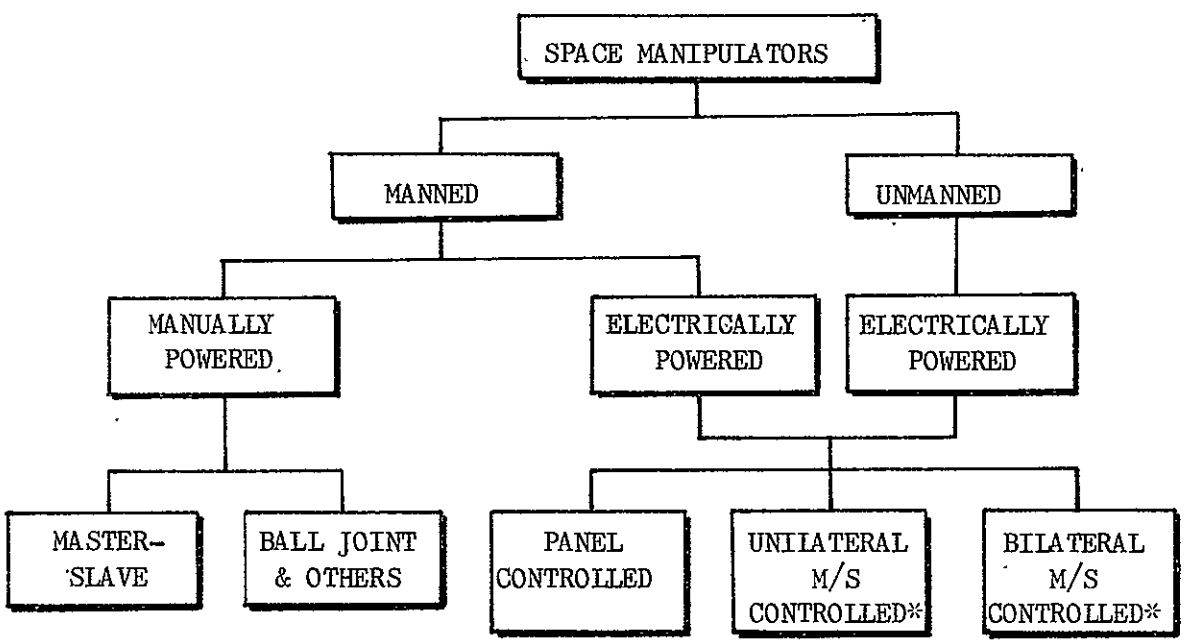
- Power requirements, both peak and average, should be low--much lower than the power required by existing manipulators. This is especially true of the electric master-slave.

- The entire manipulator should be as light as practical and occupy a minimum volume.

As can be noted in the list, the manipulator system is essentially equivalent to the extravehicular astronaut in most cases. Since the astronaut is in the control loop, the manipulator should try to use the same tools as an astronaut and follow the same work patterns and procedures as dictated by the astronaut endurance and exposure limits.

5.2.1 Suitability of Existing Manipulator Configurations for Space Systems

Only a few of the existing manipulator designs possess the characteristics that are advantageous to space operations. These configurations are shown in Figure 5-10.



*Electric Master/Slave (M/S) manipulators will normally have unilateral panel-controlled index motions in addition to their M/S motion.

FIGURE 5-10 SUITABLE SPACE SYSTEM MANIPULATORS

The pneumatically and hydraulically connected and powered manipulator systems have not been seriously considered due to the sealing problems and excessive amount of friction in the components. Existing hydraulic units are used where a rugged rate-controlled force multiplying capability is needed. As was noted previously, these excessive forces are not required for most space missions.

The ball-joint systems also present sealing and friction problems at the thru-bulkhead interfaces, and their limited number of degrees of freedom further hamper operations.

Most unilateral manipulators are slow in performing work and lack ability to accommodate to restrained paths. This would easily cause equipment damage due to their lack of force-feed and force-control.

Although there are no existing systems directly applicable to space missions, it appears that the electric powered and controlled bilateral master-slave manipulator system is the most promising for space development.

5.3 DESCRIPTION OF CURRENT SPACE SYSTEMS

The systems that will be described in this section are not state-of-the-art systems. Their development state ranges from advanced concepts to prototyped (breadboard) systems. One of the few FSAS concepts that has been developed, space qualified, and man-rated was the Astronaut Maneuvering Unit (AMU). The AMU developed for the Air Force by LTV Aerospace Corporation was to be utilized in Gemini IX A. Due to in-flight mission redefinition and problems with AMU donning, the astronaut never had the time to evaluate the device. The AMU system equipped the astronaut to operate as a miniature spacecraft for EVA operations. The system contained all of the essential subsystems that would be required for proposed space manipulator systems (e.g., transportation, stabilization, life support, etc.). Even though there are no state-of-the-art space manipulator systems at present, the materials components and subsystems required for such a system have been developed, and they or their functional equivalents have been space qualified.

The systems will be grouped and described within the classification scheme as defined in Section 5.1.2.

5.3.1 Manned Systems

As was previously noted, in the manned systems the astronaut is confined in or on a space vehicle which he controls or monitors/directs by being a primary part of the control loop of the craft. This vehicle contains all of the subsystems required for the system to perform in a free space environment (e.g., transportation, stabilization, actuation, support).

PRIME VEHICLE-MANNED (PV-M)

This approach is characterized by the following features:

- The remote manipulator(s) is mounted to the prime vehicle structure. The vehicle may be any large spacecraft such as an orbital workshop or space station.
- The astronaut providing the manipulative control function is located inside the vehicle and relies on the prime vehicle to supply his life support (shirt-sleeve environment).
- If coarse manipulatory movements are required, the prime vehicle would have to be maneuvered.

This system affords a greater amount of safety to the controlling astronaut than does any other classification because the astronaut is enclosed in the spacecraft. His surroundings provide ample protection from the hostile space environment (i.e., hard vacuum, heat/cold extremes, radiation and micrometeorites) and permit manipulator activity of long durations. Also, the controlling astronauts can be alternated. But it can also be noted that this very vehicle which houses the manipulator operator (with all of its gross systems) cannot be maneuvered with the same ease that would be afforded by a smaller remote vehicle.

To date, there are very few systems envisioned for this class. The concepts that have been developed do not encompass a complete system approach to mission performance. Most include data in areas such as actuation and translation but do not include data in the control areas (specifically man/machine integration). The "existing" systems will be described in terms of their basic characteristics and subsystems as outlined in Section 3.0.

Prime Vehicle Serpentuator System

The Prime Vehicle Serpentuator System is an advanced version of the serpentuator described in Section 4.4.1. This system, as applied to the prime vehicle class, is only in the conceptual stage of development; but most of the parameters described for the system used to support EVA also apply to the prime vehicle manipulator version. The astronaut control station would be replaced by a "robot" type subsystem containing video cameras, electrically driven bilateral actuator "arm" assemblies, etc. The man/machine interface problems would be minimized by designing these subsystems to closely resemble the human configuration (anthropomorphic and anthropometric). The control system would be more sophisticated than the EVA version, leaving few functions that would not be contained on pre-programmed modes. The astronaut would control and monitor/direct the system from a station within the prime vehicle with direct visual or video access to the worksite, if necessary. Figure 5-11 illustrates this concept.

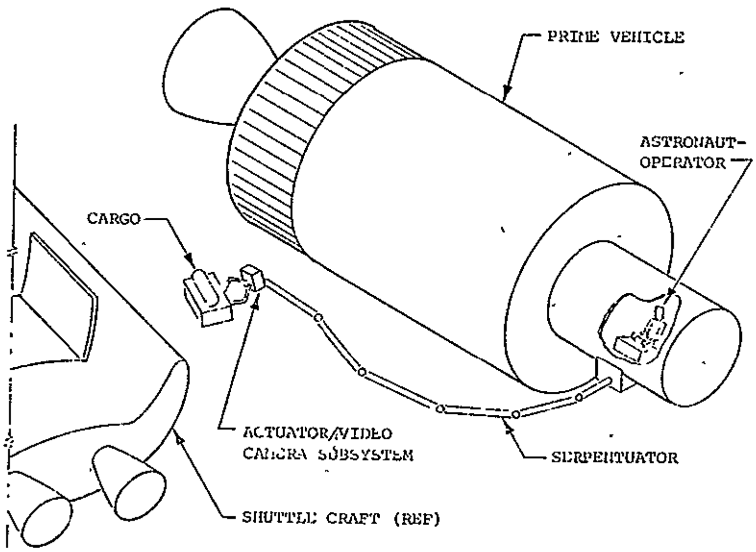


FIGURE 5-11 PRIME VEHICLE SERPENTUATOR SYSTEM

This system would be a hybrid unilateral (serpentuator-translation/stabilizer) and bilateral (actuator) manipulator configuration.

Prime Vehicle "STEM" System

The "STEM" system would be similar to the serpentuator, except that the translation/stabilization subsystem would be replaced by a STEM (Storable Tubular Extendible Member, Spar Aerospace Prod). The basic STEM concept is depicted in Figure 5-12.

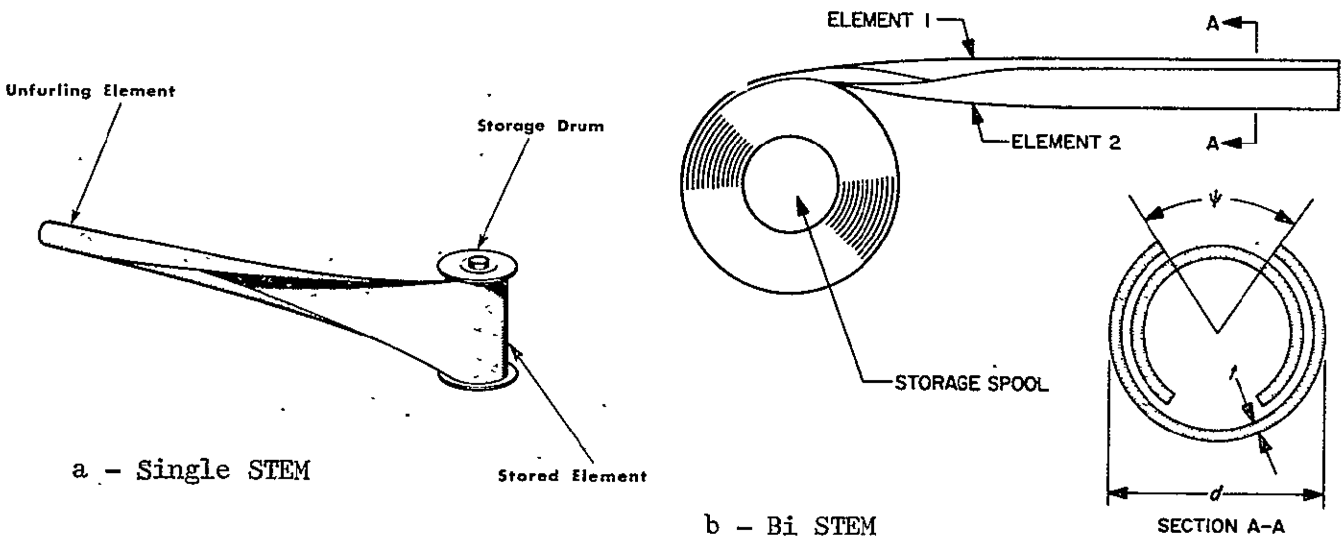


FIGURE 5-12 STEM PRINCIPLE

The STEM is a continuous strip of resilient metal which is stored flat on a storage drum. As this drum is driven, the strip changes its shape into a tubular element which is then unfurled. Many configurations are possible to stiffen the unfurled tube into a structural member (a simplified scheme is represented in the figure). By combining several STEM actuators, one can generate a subsystem for transporting an actuator. Various STEM systems have been space qualified and have flown on many Gemini and Apollo flights. One possible configuration of this system is shown in Figure 5-13. This system would be less complex than the serpentuator since it contains fewer links to be controlled.

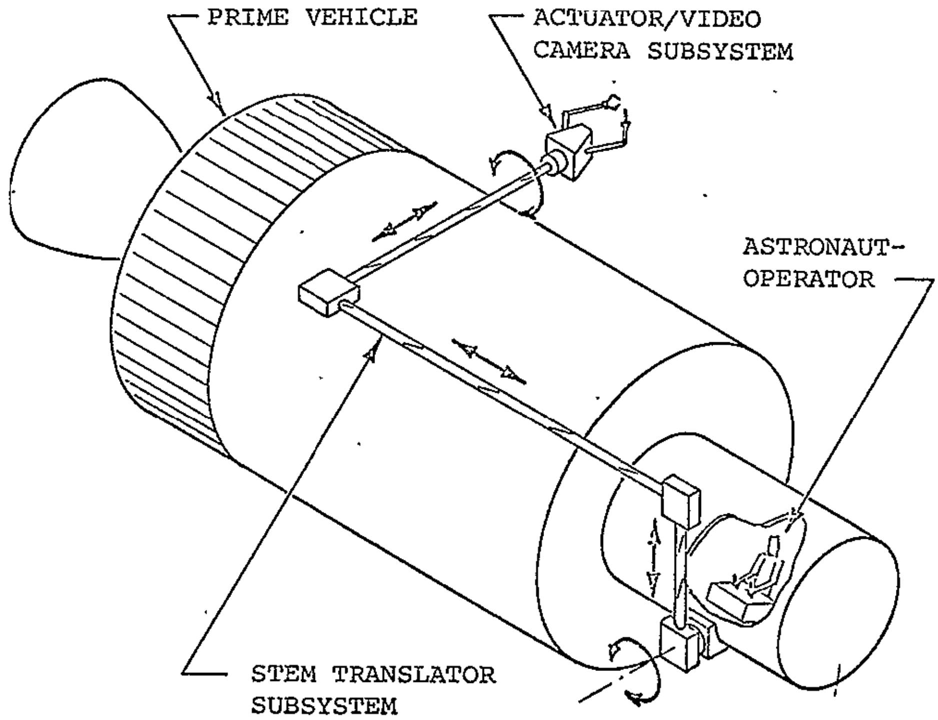


FIGURE 5-13 PRIME VEHICLE WITH STEM SYSTEM

Prime Vehicle With Manipulator Arms

It would be a simple task to mount a master-slave type manipulator to a prime vehicle and utilize the technology that has been developed in the undersea manipulator area. This type of system would be advantageous if the functions to be performed were within a restricted worksite area. Figure 5-14 illustrates this concept.

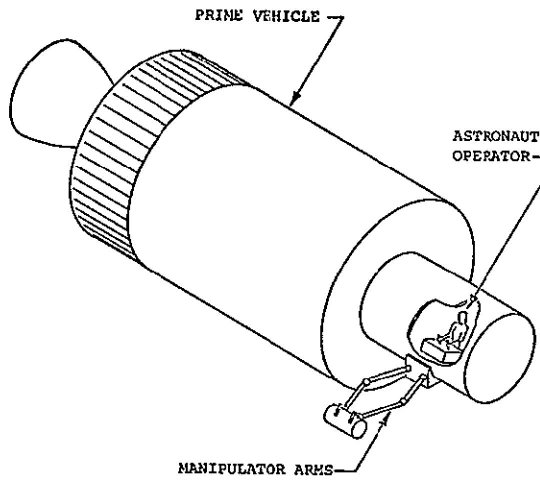


FIGURE 5-14 PRIME VEHICLE WITH MANIPULATOR ARMS

DESCRIPTION OF AUXILIARY VEHICLE MANIPULATOR SYSTEMS

The need for system development in this class has been apparent for many years. In 1960, a brief on the remote handling in space was solicited from interested aerospace companies by the Behavior Sciences Laboratory, Wright-Patterson Air Force Base. The material solicited was to be only that information which had been the result of a prior study effort by each company. A response was received from seven aerospace companies, and the survey was compiled and published in 1962. Five of these responses specified a system of the Manned Auxiliary Vehicle Manipulator Subclass. The major characteristics of these vehicles are shown in Table 5-3 (Baker, 1962). An experiment on a system with functions similar to those defined by this subclass was outlined in Advanced Technology section of "Experiment Program for Extended Earth Orbital Missions" document prepared by the NASA Advanced Manned Missions Program Office of Manned Space Flight. The object of the experiment was specified as follows:

"To investigate a simple shuttle-type space vehicle, to determine its characteristics and to define its usefulness for rescue, inter-orbital cargo transfer, crew transfer, satellite retrieval, etc., in support of a long-term orbital facility or planetary mission."

The test program specifies phases to checkout tethered and untethered maneuvers near the space station (within 200 feet) and maneuvering to a remote object to verify all operations (e.g., rendezvous, cargo transfer, etc.).

TABLE 5-3

CHARACTERISTICS OF AUXILIARY VEHICLES

CAPSULE DESIGNER \ TYPE	Anthropomorphic Glove Design	Manned	Tethered	Stabilization Arms	Window Ports For Direct Viewing	Number of Manipulator Arms
Bell	X	X	X	X	X	2
Lockheed	X	X			X	2
Douglas	X	X			X	3
G.E.		X			X	2
Norair	X	X	X	X	X	3

This subclass contains more types of manipulator systems than does any of the others described in this report. The information that is available ranges from preliminary design concepts to prototype models. The following descriptions will be grouped into these categories:

Preliminary Design Concepts

- Bell Aerosystems Remora Capsule

The REMORA configuration (Figure 5-15) is a small, buoy-shaped capsule 6-feet high, 3-feet in diameter, and weighing 540 pounds (loaded). This concept, proposed about 1960, permits one astronaut to function in space while protected from the space environment. The capsule is tethered by a cable that provides power and retrieval, if necessary, and allows a maneuvering radius of 1,000 feet. A tinted dome provides access to the capsule and allows 360° visibility. Ths capsule is oriented by reaction jets and has an operating time of 4 hours (a function of its life support system).

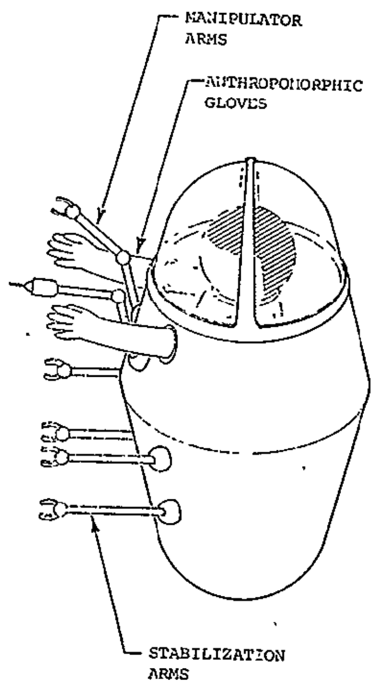


FIGURE 5-15 REMORA ORBITAL WORKER

- Douglas Aircraft Company Humpty Dumpty Capsule

The Humpty Dumpty capsule is another non-anthropomorphic concept. The craft is egg-shaped and is capable of supporting one man in space for approximately 30 hours in a self-contained environment. Three stabilizer and three manipulator arms are mounted to the outside of the craft. There are also two anthropomorphic gloves mounted on the craft through which the astronaut may perform certain functions. This concept (Figure 5-16) was also proposed about 1960.

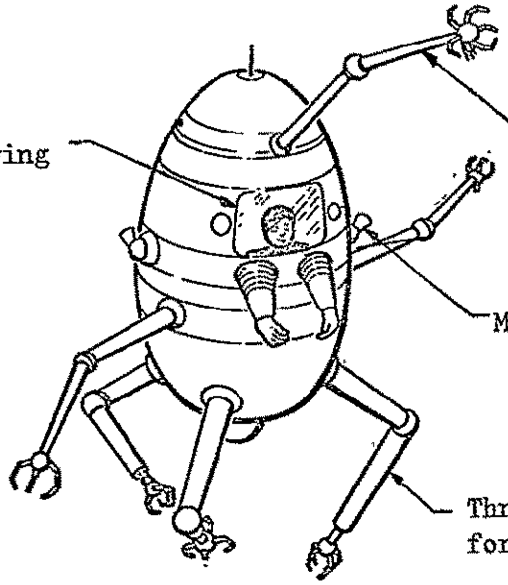


FIGURE 5-16 HUMPTY DUMPTY CAPSULE

Mockup/Prototype Design Concepts

- Bendix Corporation Module EVA Work Platform

This system proposed by Bendix and described in Section 4.4 is a configuration for an EVA work platform to be used by a suited astronaut in an orbital operation. The design consists of an assembly of five modules which are removable and interchangeable. As proposed, the astronaut conducts most of his activity from the platform; if he were equipped with a portable life support system, he could leave the platform if he desired. The platform could perform for a period of about 4 hours normally (extended to 8 hours with supplemental life support) (see Figure 5-17a).

The platform incorporates two bilateral (master-slave) manipulators. These manipulators are capable of magnifying or locking forces and extending the astronaut's reach. The manipulators have the following characteristics:

- Electrically driven
- Force amplification ratio: 2:1
- Maximum forces at slave: 25 pounds
- Working volume at master: 1 cubic foot
- Working volume at slave: approximately 525 cubic feet (5 foot radius)

- Ling-Temco-Vought Maneuvering Work Platform and Space Taxi

In 1966, Ling-Temco-Vought (LTV), in conjunction with Argonne National Laboratory (ANL), completed a thorough investigation of manned maneuvering manipulator spacecrafts for the NASA Marshall Space Flight Center. The objectives of the LTV program, called the Independent Manned Manipulator (IMM) Study, were as follows:

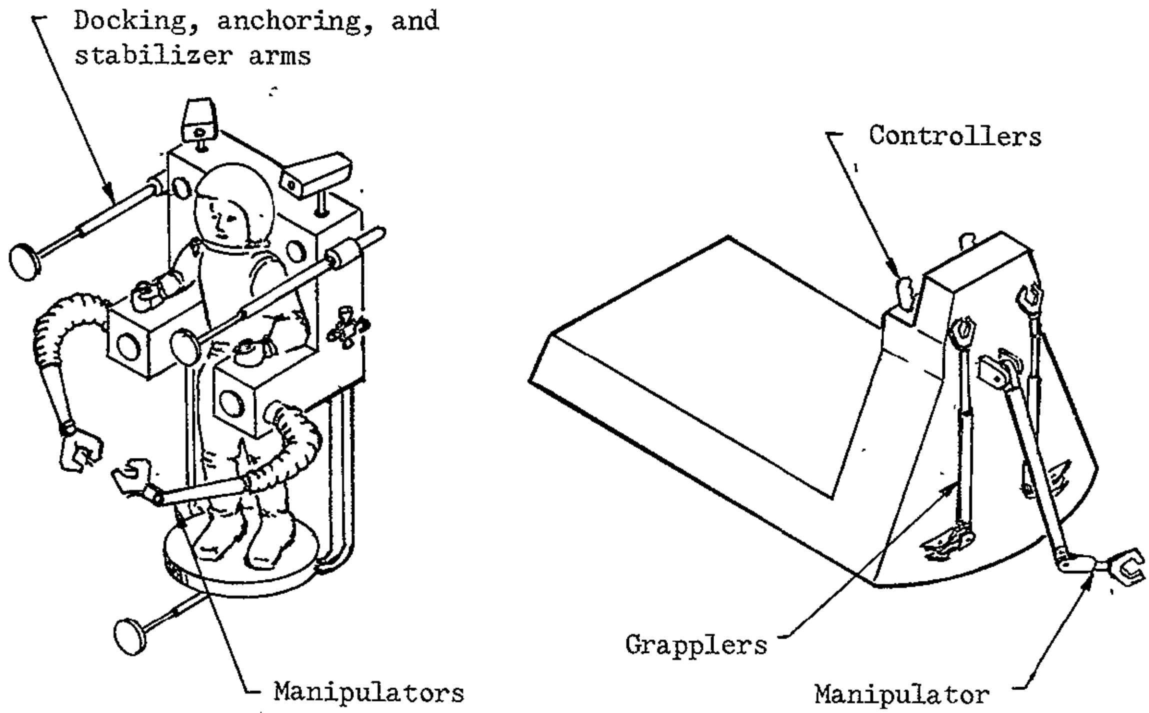
- Produce the conceptual designs and mockups of two selected IMM units which extend and enhance man's utilization in the support of AAP experiments and overall areas of EVA during future space exploration.
- Define Research, Development, and Engineering (RD&E) required to implement the IMM systems.
- Develop preliminary program definition plans which lead to flight-qualified hardware in the 1969-1971 time period.

The IMM vehicle designs were evaluated against NASA-specified criteria, and two concepts were selected for detailed analysis: the Maneuvering Work Platform (MWP) and the Space Taxi. The preliminary program definition plans were developed for obtaining the MWP flight-qualified hardware in the 1969-1971 time period and 1972-1974 for the Space Taxi.

- <u>MWP Configuration</u>

The MWP configuration selected consists of four basic modules (Figure 5-17b):

- A forward control
- An aft propulsion module
- A removable tools/spares module
- A collapsible cargo frame



a. Bendix MWP

b. LTV MWP

FIGURE 5-17 TWO EXAMPLES OF AUXILIARY VEHICLE-MANNED SYSTEM

The MWP would carry a crew of one and have a rescue capability of approximately $1\frac{1}{4}$ miles in any orbital direction. Its normal duration is 8 hours with a rescue contingency of 2 hours. The MWP is described in detail in Section 4.2.

- Space Taxi Configuration

The Space Taxi configuration, selected and recommended for use in 1975 and beyond, features a multiple crew station built into a rotary vehicle which permits orientation of each operator station relative to the worksite. Electrical bilateral master-slave manipulators were selected by AEC/ANL for incorporation into the Space Taxi configuration.

Figure 5-18 presents the preliminary design of the selected Space Taxi concept developed during the detail analysis phase. The basic vehicle consists of a cylindrical, structural shell, the center portion of which is a pressure vessel forming the crew compartment. The upper and lower unpressurized compartments contain vehicle subsystems and equipments. After worksite attachment, the basic taxi is free to turn about its longitudinal axis in rotary fashion. The rotational motion is accomplished with the upper and lower turrets which support the three anchoring and docking arms. Attached to the sides of the Taxi are the two maintenance manipulator slave arms. An Apollo docking adapter and hatch and an extravehicular maintenance egress hatch are provided. A major element inside the crew compartment is the dual function manipulator master controller. It can swing 180° to serve as the worksite anchoring arm controller and is a bilateral maintenance manipulator controller.

The Space Taxi is designed for one crewman with the capability to carry another man in a rescue situation. The craft would have a range of approximately $1\frac{1}{4}$ miles in any orbital direction. Like the MWP, its normal duration is 8 hours with a rescue contingency of 2 hours. The physical characteristics of the Space Taxi are:

- Overall length* - 150 inches

- Overall width* - 84 inches (maximum)

- Gross weight (nominal)** - dry, 3198 pounds; wet, 3474 pounds.

* Maximum stowage envelope
** Includes 732 pounds for crew systems and tools/spares

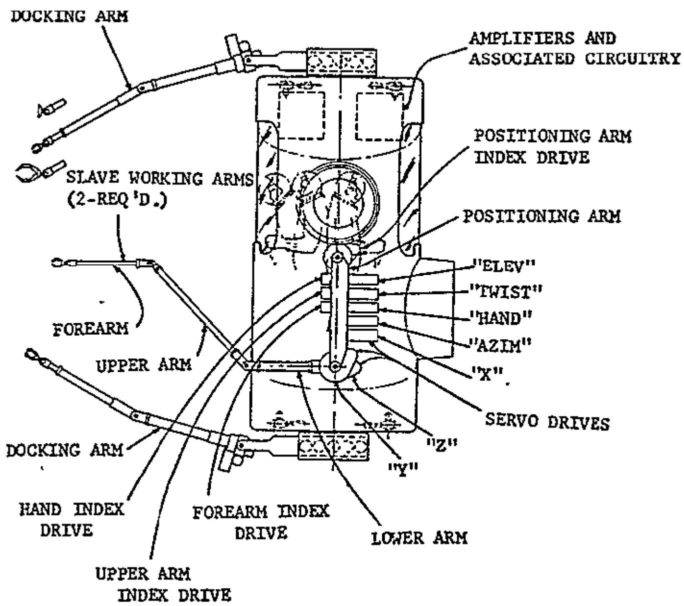


FIGURE 5-18 SPACE TAXI CONFIGURATION

<u>Translation/Stabilization/Control Subsystem</u>

The Space Taxi uses a hybrid stabilization and control system consisting of control moment gyros (CMG) and jet reaction components. Its characteristics are:

Propulsion:
- Propellant - Monopropellant hydrazine
- Total Impulse - 51,000 lb/sec.
- Total ΔV capability - 488 ft/sec.

Stabilization
and Control:

Stabilization and Control Deadband - $\pm 2^{\circ}$

Acceleration (maximum)

Angular -	Roll	- $16.3^{\circ}/sec^2$
	Pitch	- $15^{\circ}/sec^2$
	Yaw	- $40^{\circ}/sec^2$
	$\ddot{x}$	- .97 ft/sec^2
	$\ddot{y}$	- .48 ft/sec^2
	$\ddot{z}$	- .48 ft/sec^2

Number of thrusters - 24 (25 lbs. max. thrust each)

Rotational rates (maximum)

Roll	- $13.1^{\circ}/sec.$
Pitch	- $12^{\circ}/sec.$
Yaw	- $31.8^{\circ}/sec.$

Actuator Subsystem

The actuator subsystem consists of three electrically connected bilateral docking and anchoring arms used for stabilization at the worksite and two electrically connected bilateral manipulators used for tasks at the worksite.

Environmental Control Subsystem

The Space Taxi ECS/LS system provides a 5 psia, 70/30 percent, oxygen-nitrogen atmosphere for closed-cabin operation.

ECS/LS Duration -	Nominal	8 hours
	Contingency	2 hours
Metabolic Rates -	Average	1250 Btu/hr.
	Peak	In excess of 2150 Btu/hr.

Total heat load capability - 47,703 Btu

Repressurization cycles - 2

A Space Taxi weight summary is shown in Table 5-4.

TABLE 5-4

SPACE TAXI WEIGHT SUMMARY

SUBSYSTEM	WEIGHT(LBS)		
Propulsion System	78.0		
ECS/LS System	394.0		
Electric Power System	173.7		
Communications System	70.9		
Stability & Control System	251.5		
Radar System	8.0		
Manipulators & Grappler System	920.0		
Controls and Displays	40.0		
Structure	530.0		
Subtotal (Dry)		2,465.6	
Expendables			
Propellant	234.0		
N_2 ..... 3.94			
O_2 ..... 16.81			
H_2O 12.00			
H_2 ..... 0.60			
Freon... 9.00	42.3		
Subtotal		276.3	
WEIGHT (Wet)			2,741.9
Crew System			
Crewman	193.0		
Pressure Suit	67.0		
PECS	82.0		
Subtotal		342.0	
Tools and spares		390.0	
TOTAL WEIGHT			3,473.9

5.3.2 Unmanned Auxiliary Vehicle Systems

A system of this class is described in the Experiment Program for Extended Earth Orbital Missions document (Ref: Experiment data sheet VI-B). The object of the experiment (remote maneuvering/manipulator system) was:

> "To evaluate the effectiveness of unmanned remotely controlled manipulator-equipped, maneuvering units for performing orbital extravehicular activities (EVA)."

The system outlined for this program had the following characteristics:

- Controlled from a space station
- Range of 6000-7000 feet
- Ability to dock, remove, replace, and assemble in orbit
- Have two electrical bilateral master/slave manipulators

The system outlined in this NASA document describes a spacecraft that has been proposed by the General Electric Company. This system will be described subsequently.

LOCKHEED SPACE CARGO HANDLER AND
MANIPULATOR FOR ORBITAL OPERATIONS (SCHMOO)

The SCHMOO system was described to the 1964 proceedings of the 12th Conference on Remote Systems Technology as an unmanned vehicle capable of performing operations on a remote hostile spacecraft (i.e., a nuclear power type) while being controlled from an earth or orbiting base station (Vivian, 1964).

The SCHMOO, as shown in Figure 5-19, is an oblate spheroid with a width of 15 feet, length of 18 feet, and height of 12 feet. Its dry weight is approximately 7,500 pounds, and its wet weight is 11,300 pounds.

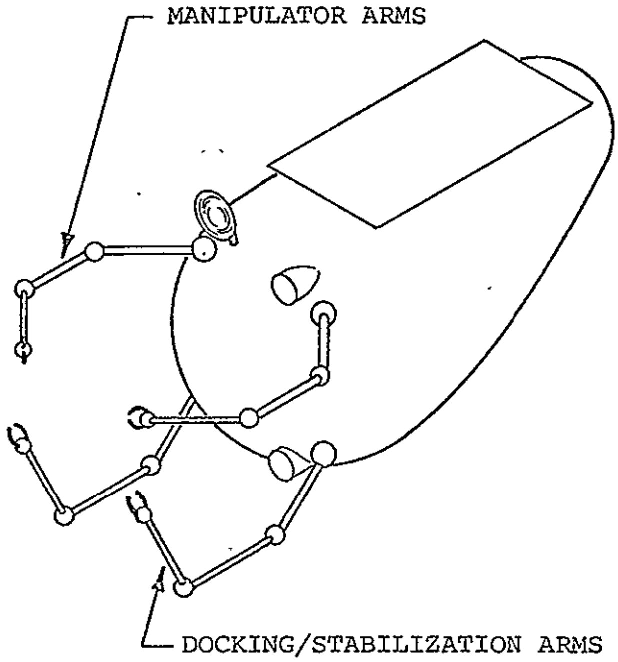


FIGURE 5-18 LOCKHEED SCHMOO SYSTEM

Subsystem Description

Translation/Stabilization/Control Subsystem

Propulsion - This system consists of two pressure-fed hypergolic, bi-propellant reaction jets, each capable of delivering 200 pounds of thrust.

Attitude Control Propulsion - The attitude control system utilizes the same propellants as the propulsion units. It has 16 thrusters clustered in groups of four which provide the attitude and control. Their levels range from ½ to 1 pound.

Control - The control system for SCHMOO is comprised of two independent but cooperative subsystems. One is a computer-controlled guidance and attitude control system. It used a precision narrow beam (1 degree) radar in conjunction with the three-dimensional television monitor for locating the target vehicle, determining closure trajectory, closing, and attaching

SCHMOO to the target vehicle. The computer is located on-board to reduce the number of communication channels required to operate SCHMOO.

The other control subsystem, which uses the same computer as used in guidance, is concerned with the operation of the manipulators. The manipulator control is a digital position differential system with a position control and monitoring accuracy of 0.1 percent. It has a rate application, within mechanical system limits, proportional to the error differential.

Actuator Subsystem

The vehicle is equipped with four articulated manipulator arms. Two arms are located on the lower portion of the vehicle and are used for docking and stabilizing the vehicle at the worksite. The other two provide the manipulative capability. The SCHMOO arms are patterned after the General Mills Model 500 manipulators. A description of the arms is given in Table 5-5.

TABLE 5-5

SCHMOO MANIPULATOR/ATTACHMENT ARM CHARACTERISTICS

SECTION	MANIPULATOR ARMS - MECHANICAL DESCRIPTION				ATTACHMENT ARMS - MECHANICAL DESCRIPTION			
	Range	Rate	Force	Length	Range	Rate	Force	Length
SHOULDER								
Extension	18 in.	120 in/sec	600 lb.	-	-	-	-	-
Rotation	Continuous	1 rpm.	-	-	Continuous	1 rpm.	-	-
Pivot	250°	1 rpm.	-	-	250°	1 rpm.	-	-
UPPER ARM	-	-	-	6 ft.	-	-	-	6 ft.
ELBOW								
Rotation	Continuous	2 rpm.	-	-	Continuous	2 rpm.	-	-
Pivot	270°	1.5 rpm.	-	-	270°	1.5 rpm.	-	-
FOREARM	-	-	-	6 ft.	-	-	-	8 ft.
WRIST								
Extension	4 in.	45 in/min.	100 lb.	-	-	-	-	-
Rotation	Continuous	8 rpm.	-	-	Continuous	8 rpm.	-	-
Pivot	310°	2 rpm.	-	-	310°	2 rpm.	-	-
HAND								
Length	-	-	-	4 ft.	-	-	-	4 ft.
OPENING	5 in.	20 in/min.	150 lb.	-	5 in.	20 in/min.	150 lb.	-

Visual Comminications Video

The SCHMOO is equipped with two complete, independent television systems which provide both visual monitoring of the final stages of approach to a target and observation of the tasks performed by the manipulators. One has three-dimensional color transmission with two camera pods mounted on opposite sides of the radar tracking antenna and interconnected so that adjustment of focal length automatically adjusts parallax. The second system employs two independent two-dimensional black-and-white camera pods located on the "backs" of the manipulator hands for direct monitoring of the hands; this system also can be used as a backup for the three-dimensional color system without automatic parallax control.

G.E. REMOTE MANIPULATOR SPACECRAFT

In June of 1969, the General Electric Company published their final report on "A Study of Application of Remote Manipulation to Satellite Maintenance" (Interim, 1969). In this NASA-sponsored program, G.E. proposed that a manipulator spacecraft be developed to perform in-orbit EVA operation (i.e., repair, refurbishment, etc.). Two significant design philosophies for the vehicle are:

- The spacecraft manipulator should be "man-equivalent," i.e., it should have the force, reach, and response of a typical man and therefore be interchangeable with him.

- The system should be controlled from an external, remote location and be developed for a single mission for a low-cost approach. They state that by producing larger quantities, the recurring cost can be lowered and the single mission system would have a shorter operating life.

Figure 5-20 depicts G.E.'s earlier remote manipulator spacecraft concepts. The configuration that appears to reflect G.E.'s latest thinking is shown in Figure 5-21.

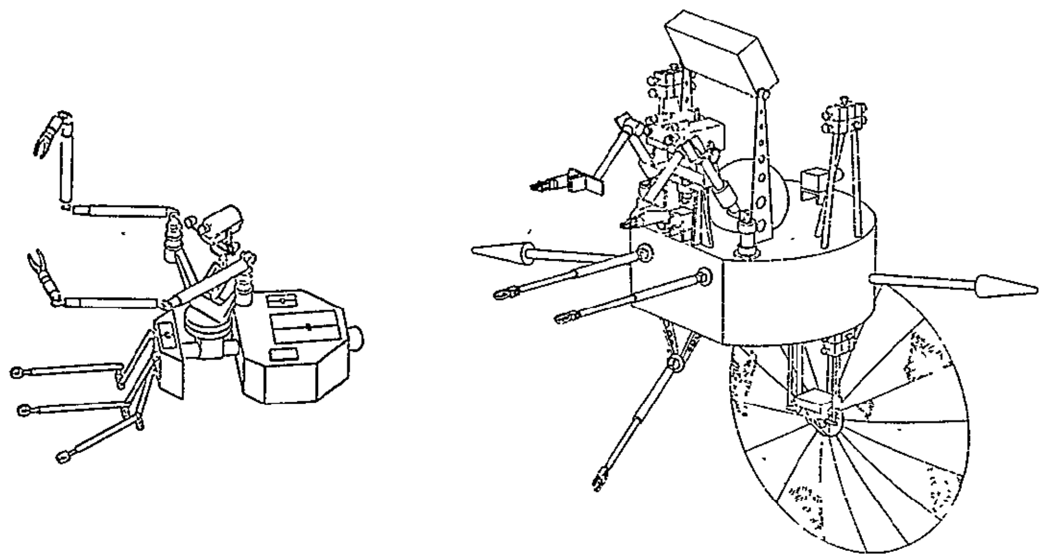


FIGURE 5-20 GENERAL ELECTRIC'S
EARLY REMOTE MANIPULATOR SPACECRAFT

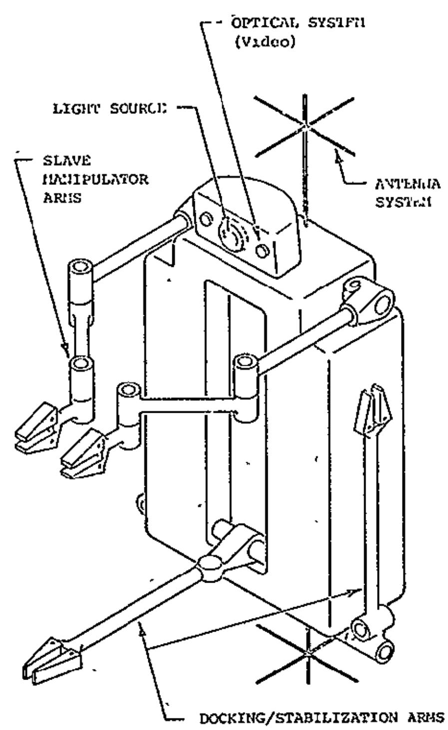


FIGURE 5-21 G.E. REMOTE MANIPULATOR SPACECRAFT

The spacecraft has an approximate weight of 530 pounds and is approximately 12 inches deep by 40 inches wide by 75 inches high (including antennas). It has two electric bilateral manipulator arms that are slave to a master control system in a remote site. The system has a payload capability of about 500 pounds and a mission duration of 10 hours (Interim - Kugath, 1969).

Subsystem Description

Translation Subsystem

The propulsion is accomplished by a common blow-down monopropellant hydrazine subsystem. It would have large rendezvous engines for translation to the worksite and smaller thrusters for attitude control and maneuvering.

Stabilization/Control Subsystems

The attitude-control subsystem functions in two modes: 1) it stabilizes only the remote manipulator spacecraft; and, 2) it also stabilizes the worksite (docked satellite). The attitude reference is supplied by a three-axis, rate-integrating gyro package. A momentum storage device reduces the thruster usage at the worksite.

The spacecraft maneuvers are performed automatically; the inputs to the guidance computer are produced by the video subsystem and the internal-reference package.

The optical (video) system consists of two cameras which 1) give the operator a three-dimensional display, 2) provide redundancy in case of a camera failure, and 3) serve as range finder to supply data to guidance/control subsystem for rendezvous and docking.

Actuator Subsystem

This subsystem consists of three docking/stabilization arms and two manipulator arms. The manipulators are bilateral, slave type that resemble the human arms but are not anthropomorphous. The manipulator characteristics are shown in Table 5-6 and dimensions are given in Figure 5-22. Table 5-7 gives the weights and estimated power requirements for the remote manipulator spacecraft.

TABLE 5-6

MANIPULATOR CHARACTERISTICS

PARAMETER	DESCRIPTION
Configuration	Two six-degree-of-freedom arms
Type	Electrical bilateral, i.e., closed loop position control with force feedback
Reach	40 inches, spherical envelope
Resolution	0.04 inches
Force	15 lb per arm at maximum reach
End Effector	Parallel jaw tongs
Indexing	Two shoulder joints

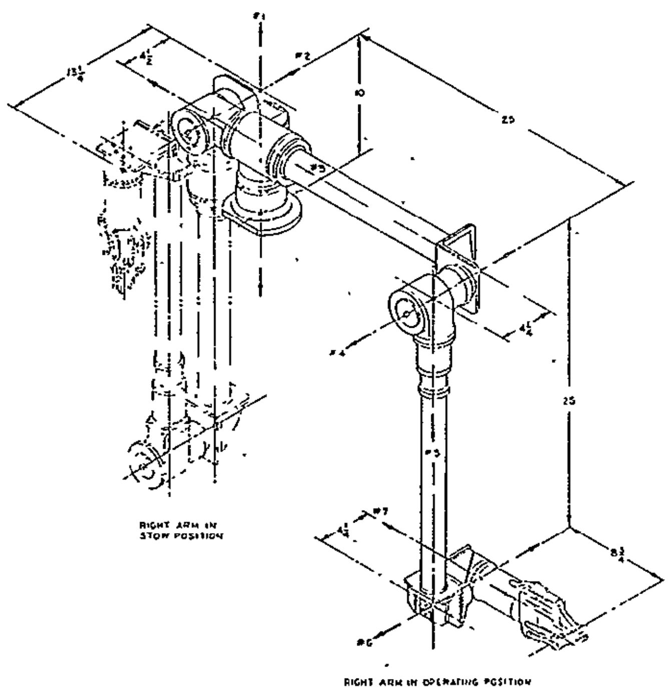


FIGURE 5-22 ISOMETRIC OF SLAVE MANIPULATOR

TABLE 5-7

WEIGHT AND POWER REQUIREMENTS FOR
THE G.E. REMOTE MANIPULATOR SPACECRAFT

SUBSYSTEM	WEIGHT, LB.	POWER, WATTS
Manipulator		peak each
Manipulators (2)	29.0 (each)	300.0 (21.5 avg)
Amplifiers (14)	2.0 (each)	-
Docking tethers (3)	6.0 (each)	-
Total	104.0	600.0 peak (43 avg)
Video		
Camera-head assemblies (2)	1.0 (each)	-
Electronics (2)	5.5 (each)	15.0 (each)
Lens (2)	6.5 (each)	2.0 each peak (nil.avg)
Mirrors & Servos (2)	4.0 (each)	2.0 each peak (1 each)
Lamp	1.0	10.0 (avg)
Cables, etc.	3.0	-
Total	38.0	48.0 peak (42 avg)
Guidance & Control		
Flywheels (3, includ. elec.)	13.0 (each)	15.0 each peak (5 each)
Gyro pkg. (includ. elec.)	17.8	38.9 (avg)
Total	56.8	83.9 peak (53.9 avg)
Propulsion		
Tank with bladder	5.7	-
Valves	1.6	-
Thrusters with valves	2.2	20.0 peak (nil.avg)
Electronics	0.5	5.0
Structure & plumbing	1.5	-
Propellant (NH_4)	10.0	-
Pressurant (GN_2)	0.5	-
Total	22.0	25.0 peak (5 avg)
Communications		
PAM-commulators (3)	1.3 (each)	1.8 (each)
Subcarrier oscillators (2)	0.2 (each)	0.3 (each)
Mixer amplifier (2)	0.2 (each)	0.8 (each)
500-MHZ transmitters (2)	1.2 (each)	2.0 (each)
Digital command subsystem (1)	20.0	11.0
Multiplexer (1)	2.0	-
Total	29.1	23.2
Power	165.0	-
Thermal control	5.0	-
Structure	75.0	-
Harnessing	38.0	-
GRAND TOTAL	532.9	780.1 peak (167.1 avg)

SECTION VI

TRADEOFF METHODOLOGY

6.0 TRADEOFF METHODOLOGY

One primary objective of this effort was to develop a methodology to assist system design engineers in the performance of cost/effectiveness tradeoffs of feasible free space activity system concepts. This methodology is contained in a design guide handbook published under separate cover and intended to serve as a comparison document to this report.

Before discussing the methodology in detail, some consideration will be given to selection of manual EVA versus remote systems to perform extravehicular functions.

6.1 MAN & MANIPULATOR

In the development of the tradeoff methodology, system effectiveness parameters were developed for each EV function. These parameters were generated based on the requirements identified for each function (presented in Table 2-2). In order to isolate the primary advantages and disadvantages of manual EVA and remote systems, each primary FSAS class was rated on each parameter. The following ratings were established:

<u>Value</u>

0 - no capability

1 - minimal capability--basic problems

2 - moderate capability--technical problems

3 - good capability--minor problems

4 - excellent capability--no known problems

The ratings for each system class on each parameter, as made by the authors, are presented in Table 6-1. The parameters are of two types: those general to all EV functions and those specific to functions. The parameters which are general to functions are categorized by FSAS subsystem, while the specific parameters are classified by function. The classes of FSAS employed include:

- Manual EVA - unaided (manual translation and actuation)
- Manual EVA - aided (aided translation and/or actuation)
- Remote System - prime vehicle - manned (PV-M - manipulator on prime vehicle)
- Remote System - Auxiliary vehicle - manned (AV-M - manipulator on enclosed satellite vehicle)
- Remote System - Auxiliary vehicle - unmanned (AV-M - manipulator or unmanned remote maneuvering vehicle)

As indicated by Table 6-1, the only categories of general parameters where unaided manual EVA is more effective than any remote concept include control and physical characteristics. Aided EVA is at least as effective as the remote concepts on translation, stabilization, control, and actuation. A summary of the effectiveness of manual EVA vs remote systems on parameters general to all functions is as follows:

- Translation - unaided EVA inferior to all other classes
- Stabilization - unaided EVA inferior to all other classes
- Control - unaided EVA superior to all other classes
- Actuation - unaided EVA inferior to all other classes
- Support - unaided EVA inferior to all other classes, PV-M superior to all other classes
- Physical characteristics - unaided EVA and PV-M superior to all other classes
- Environmental control - unaided EVA inferior to all other classes

TABLE 6-1

RATINGS OF FSAS CLASSES ON
SYSTEM EFFECTIVENESS PARAMETERS

KEY: Rating
- 0 - no capability
- 1 - min. capability--basic problems
- 2 - mod. capability--tech. problems
- 3 - good capability--minor problems
- 4 - excellent capability--no known problems

PARAMETERS GENERAL TO ALL FUNCTIONS		SYSTEM CLASSES: MAN		REMOTE SYSTEM		
Function	Parameter	UNAIDED	AIDED	PV-M	AV-M	AV-UM
Translation	Translation range	1	3	2	3	3
	Translation velocity	1	3	2	3	3
	Control of translation direction	1	2	2	2	2
	Control of translation velocity	3	3	2	3	2
	View of translation route	4	3	2	3	2
	Field of view while translating	4	3	2	2	2
	Astronaut orientation	2	2	4	2	4
	Astronaut support required	1	1	4	2	4
	Astronaut energy expenditure	1	2	4	3	4
	SUM	18	22	24	23	26
Stabilization	Stabilization while translating	2	4	4	4	4
	Stabilization at worksite	2	3	3	3	4
	Interface with structures	2	3	2	3	4
	SUM	5	10	9	10	12
Control	Repeatability of tasks	2	2	4	4	3
	Adaptability to several worksites	3	3	3	2	2
	Feedback available	4	4	3	3	2
	Capability of viewing workspace	4	4	3	3	3
	Operational time	2	3	2	2	2
	Flexibility	4	3	2	2	2
	Data management	2	3	4	3	2
	Unstow/deploy time	4	2	3	2	2
	Checkout time	4	2	2	2	2

TABLE 6-1 (Continued)

PARAMETERS GENERAL TO ALL FUNCTIONS		SYSTEM CLASSES: MAN		REMOTE SYSTEM		
Function	Parameter	UNAIDED	AIDED	PV-M	AV-M	AV-UM
Control (Continued)	Actuation time	3	3	2	2	2
	Precision capability	4	4	2	2	2
	Complexity of control operations	3	3	2	2	2
	Engineering complexity	4	3	2	2	2
	Number of crewmen	2	3	3	3	3
	SUM	45	42	37	34	31
Actuation	Mass handling capability	2	3	3	3	2
	Degree of worksite prep. required	2	3	3	3	3
	Range of motions	3	3	2	2	2
	Number of actuators	3	3	3	3	3
	Adaptability to tools	3	3	2	3	3
	Force directions	2	3	3	3	3
	Force magnitudes	2	3	3	3	3
	Reach envelope	2	3	3	3	3
	SUM	19	24	23	23	22
Support	Maintainability	3	2	3	2	2
	Safety features	1	2	3	2	2
	Backup systems	2	2	3	2	2
	Malfunction detection	2	3	3	3	3
	Malfunction isolation	2	3	3	3	3
	Malfunction correction	2	3	3	3	3
	Lighting of translation route	2	3	3	3	3
	Lighting of worksite	3	3	3	3	3
	Backup lighting	3	3	2	2	2
	Protective guards	2	2	3	2	2
	Umbilical management	2	2	4	4	4
	Emergency provisions	2	2	3	2	2
	SUM	26	30	36	31	31
Environmental Control	Primary system	2	2	3	2	2
	Backup system	2	2	3	2	2
	Capability of integ. ECS & trans. s. subsys.	2	3	4	4	4
	SUM	6	7	10	8	8

TABLE 6-1 (Continued)

		SYSTEM CLASSES				
		MAN		REMOTE SYSTEM		
		UNAIDED	AIDED	PV-M	AV-M	AV-UM
PARAMETERS GENERAL TO ALL FUNCTIONS						
Function	Parameter					
Physical Characteristics	Weight	4	3	3	2	2
	Power	3	2	3	2	2
	Fuel requirements	4	2	4	2	2
	Expendable requirements	3	2	3	2	2
	Storage volume	4	2	3	2	2
	Deployed volume	4	2	3	2	2
	Interface with structures	2	3	3	3	3
	Interface with worksite	2	3	3	1	3
	State of development	4	2	3	1	1
	SUM	30	21	28	19	19
PARAMETERS RELATED TO SPECIFIC FUNCTION						
Function	Parameter					
Deploy	Capability to perform	2	3	2	3	2
	Trans. capability while deploy	2	3	2	3	3
	Capability of 2-handed operation	3	3	3	3	3
	Verif. of deployment completion	3	3	2	3	2
	Capability of viewing entire structure	3	3	2	3	2
	Constraints on deployment	2	3	2	3	2
	SUM	15	18	13	18	14
Remove/Replace	Capability to perform	3	3	3	3	2
	Size/mass limits of packages	2	3	2	3	3
	Provisions for temp. storage	3	3	3	3	2
	Capability of aligning replace.	3	3	3	3	2
	Capability of viewing access	4	4	2	3	3
	Number of operations	3	3	2	3	2
	Capability of unlocking	3	3	3	3	3
	Capability of verifying	4	3	2	3	2
	Constraints on remove/replace	3	3	3	3	3
	SUM	28	28	23	27	22

TABLE 6-1 (Continued)

PARAMETERS RELATED TO SPECIFIC FUNCTIONS

Function	Parameter	MAN UNAIDED	MAN AIDED	REMOTE SYSTEM PV-M	REMOTE SYSTEM AV-M	REMOTE SYSTEM AV-UM
Cargo Transfer	Capability to perform	2	3	3	3	3
	Mass limits of cargo	2	3	3	3	3
	Transfer range	1	3	2	3	3
	Feedback on cargo status	3	3	2	3	2
	Time to load	2	2	3	2	2
	Loading operations	2	2	3	2	3
	Cargo stabilization	2	3	3	3	3
	Rate of transfer	2	3	3	3	3
	Transfer direction control	2	3	2	3	3
	Flex. of modifying direction	1	3	2	3	3
	Malfunction detection	2	3	3	3	3
	Constraints	1	3	2	3	2
	SUM	22	34	31	34	33
Inspect	Capability of performing	3	3	2	2	2
	Visual acuity	3	3	2	3	2
	Tactual feedback	3	3	1	1	1
	Pattern recognition	3	3	2	2	2
	Connection verification	3	3	2	2	2
	Operation verification	3	3	3	3	2
	Inspect. capability while transl.	2	3	3	3	3
	Constraints	3	3	2	3	3
	SUM	23	24	17	19	17
Maintain	Capability of performing	3	3	2	3	2
	Capability of service-refurb.	2	3	2	3	3
	Capability of cleaning	3	3	2	3	2
	Capability of filling	2	3	2	3	3
	Capability of focusing	4	3	2	3	2
	Capability of aligning	3	3	2	3	2
	Capability of calibrating	3	3	2	3	2
	Capability of checking out	3	3	3	3	2
	Capability of tightening	3	3	3	3	3
	Feedback available--visual	3	3	2	3	2
	Feedback available--tactual	3	2	2	2	2

TABLE 6-1 (Continued)

PARAMETERS RELATED TO SPECIFIC FUNCTIONS		SYSTEM CLASSES: MAN		REMOTE SYSTEM		
Function	Parameter	UNAIDED	AIDED	PV-M	AV-M	AV-UM
Maintain (Continued)	Time to maintain	3	2	2	2	2
	Worksite equip. malfunc. detect.	3	3	2	3	2
	Tool interface	3	3	3	3	3
	Constraints	2	3	2	3	2
	SUM	43	43	33	43	34
Assembly	Capability of performing	2	3	3	3	3
	Capability of attaching	3	3	2	2	2
	Capability of installing	3	3	2	3	2
	Capability of subassem. mating	2	2	3	3	3
	Capability of subassem. handling	2	2	3	3	3
	Capability of subassem. erection	2	2	3	3	3
	Capability of assembly test	2	2	3	3	2
	Tool interface	3	3	3	3	3
	View of workspace	4	4	3	4	3
	Mass handling capability	2	3	3	3	3
	Capability of moving assemblies	1	3	2	3	3
	Time to assemble	2	3	2	3	2
	Constraints	2	3	2	3	2
	SUM	30	36	34	39	34
Repair	Capability of performing	2	3	3	3	3
	Capability of patching	2	3	2	3	2
	Capability of cutting	2	3	3	3	3
	Capability of component replacement	3	3	3	3	3
	Capability of electrical repair	2	3	3	3	3
	Capability of mechanical repair	2	3	4	3	3
	Capability of line-valve repair	2	3	4	3	3
	Verification of repair	3	3	2	3	2
	Time to repair	2	3	2	3	2
	Constraints	2	2	2	3	2
	SUM	22	29	36	30	26

TABLE 6-1 (Continued)

PARAMETERS RELATED TO SPECIFIC FUNCTIONS		SYSTEM CLASSES: MAN		REMOTE SYSTEM		
Function	Parameter	UNAIDED	AIDED	PV-M	AV-M	AV-UM
Operate/ Monitor	Capability of performing	2	3	3	3	2
	Time to activate	3	3	2	3	2
	Time to interrupt operations	3	3	2	3	2
	Duration of operations	2	2	4	3	3
	Ease of monitoring operations	2	2	3	3	3
	Constraints	2	3	2	3	2
	SUM	14	16	16	18	14
Data Acquisition	Capability of performing	3	3	2	3	2
	Capability of photographing	4	3	2	3	2
	Capability of recording	3	3	2	3	2
	Capability of measuring	4	3	2	3	2
	Capability of translating	2	4	2	4	3
	Constraints	2	3	2	2	2
	SUM	18	19	12	18	13
Satellite Recovery	Capability of performing	0	3	2	3	3
	Capability of Rendezvous	0	3	1	3	3
	Capability of satellite inspection	2	3	2	3	4
	Capability of stabiliz. of satellite	0	3	3	3	3
	Capability of capturing	0	3	3	3	2
	Capability of securing	0	3	3	3	2
	Capability of satellite tracking	2	3	2	3	2
	Rendezvous range	0	1	1	3	4
	Verification	0	3	2	3	2
	Feedback	0	3	2	3	2
	Constraints	0	3	2	3	2
	SUM	4	31	23	33	29
Astronaut Excape/Rescue	Capability to perform	1	3	2	3	2
	Capability of despinning astronaut	1	2	2	2	2
	Capability of carrying astronaut	1	3	2	3	2
	Capability of assisting excape	3	3	2	3	2
	Capability of providing expend.	1	3	2	3	3
	Capability of extricating trapped ast.	1	3	3	3	3
	Constraints	1	3	2	3	2
	SUM	9	20	15	20	16

In terms of parameters associated with functions, the following conclusions may be formulated:

- Unaided EVA is incapable of performing satellite recovery and is only marginally capable of performing astronaut rescue.
- Functions on which manual EVA (aided and unaided) is judged to be a more effective means than remote systems include:
  - Inspection
  - Maintenance
  - Data acquisition
- Functions on which the remote means are probably more effective than normal approaches include:
  - Cargo transfer
  - Assembly
  - Repair
  - Satellite recovery
  - Astronaut escape and rescue

Advantages and disadvantages of the candidate approaches can be identified by means of an analysis of the parameters on which each class is most effective and least effective. The summary of this analysis is presented in Table 6.2.

TABLE 6-2

PRIMARY ADVANTAGES AND DISADVANTAGES OF CLASSES

CLASS	ADVANTAGES	DISADVANTAGES
Manual Unaided	Visibility envelope Versatility at worksite Dexterity Minimum engineering complexity Stage of development Maintenance requirements	Limited range Translational velocity Limited directional control Support requirements Safety hazards Limited mass handling Limited cargo transfer Astronaut energy expenditures

TABLE 6-2 (Continued)

CLASS	ADVANTAGES	DISADVANTAGES
Manual Aided	Versatility at worksite Good cargo transfer Good feedback Dexterity Good translative capability Good actuation capability Package handling capability	Support requirements Safety hazards Backup translation Weight, power, volume
Prime Vehicle - Manned	Minimal energy expenditures Minimum astronaut support Task repeatability Data management capability Minimal requirements for expendables Good repair capability Longer duration of operations Package handling capability Astronaut safety	Limited accessibility Dexterity Time to perform Feedback problems Limited inspection capability Limited maintenance capability Limited rescue capability Stage of development
Auxiliary Vehicle - Manned	Repeatability of operations Cargo transfer capability Package handling capability Maintenance capability Assembly capability Satellite recovery capabilities Astronaut rescue Data acquisition capability	Worksite adaptability Weight, power, volume Limited feedback Stage of development Support requirements Backup translation Weight, power, value Maintenance requirements
Auxiliary Vehicle - Unmanned	Minimal energy expenditure Minimal astronaut support Translation capability Astronaut safety Cargo transfer capability Assembly and repair capability Satellite recovery Inspection capability	Control capability Maintenance requirements Weight, power, volume Stage of development Maintenance required

The general conclusions to be drawn from the man vs manipulator tradeoff are:

- Unaided manual EVA should not be seriously considered except as a contingency mode due to problems with safety, support, energy expenditures, and cargo transfer.

- Unmanned maneuvering systems (AV-UM) are generally limited in terms of their capability to perform EV functions.

- Aided manual EVA and auxiliary vehicles - manned are most effective over all functions. From a performance effectiveness standpoint, selection of either of these two classes is recommended.

- Aided manual EVA meets most requirements associated with the function and, aside from unaided manual, is furthest along in development of any class.

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SECTION VII

WORKBOOK METHODOLOGY

7.0 WORKBOOK METHODOLOGY

7.1 INTRODUCTION

The primary goal of this study was to develop a procedure which could be used by space mission planners and spacecraft designers in selecting a means to perform extravehicular activities. The procedure was to take account of mission requirements, EVA system performance effectiveness, and system costs. It was to be simple enough for use by planners and designers who had little or no knowledge of remote manipulator or astronaut capabilities and limitations.

Volume I of this study, entitled "Performance Effectiveness Evaluation Schemes" or PEEVS, meets this primary goal.

7.2 PERFORMANCE EFFECTIVENESS EVALUATION SCHEME

Performance Effectiveness Evaluation Scheme is a three-phase process of elimination. In the first phase, the user selects those extravehicular systems which generally meet his mission requirements. In the second phase, those systems at the highest development levels are selected for further analysis. In the third phase, a detail cost/effectiveness trade-off is performed on all extravehicular systems identified through phases 1 and 2. The result is an identification of one or more extravehicular systems most suitable to the particular mission.

7.2.1 PEEVS Assumptions

In leading the user to the selection of an extravehicular system, PEEVS makes several assumptions:

- That the user knows the EV requirements of his mission
- That he can translate these into the PEEVS set of EV functions
- That he can identify the performance effectiveness and cost measures related to the functions of the mission

- That he can rank order performance effectiveness and cost measures with respect to impact on total mission success.

The first three assumptions are "strong" in that the process cannot work effectively without them. The fourth is "weak" because the process permits the user to test the impact of its violation on the results and suggests several remedial courses of action if the impact is great.

7.2.2 Detail PEEVS Procedure

In order to perform the three-phase process of elimination, the user executes a seven-step procedure. Six steps are required, and the seventh is optional. The decisions required and data flow over these seven steps are shown below:

STEP I - The user reviews each of twelve system functions, listed in Workbook Section 3.0, and identifies those which represent his mission.

STEP II - For each identified function the user reviews performance effectiveness measures, listed in Workbook Section 4.0, and selects those which are relevant to his mission.

STEP III - Each of the systems reviewed during the study was classified into one of twenty-one (21) system classes. During this study, Matrix reviewed each system class with respect to each performance measure on system function. As a result each system class received a "favorable-unfavorable" rank with respect to a specific performance measure/function combination.

In Step III the user counts the number of times each of the twenty-one (21) system classes has been ranked "favorable" across his selected performance measure/function combinations (rankings are found in Section 5.0 of the workbook). Then he selects at least five system classes with the highest number of "favorable" rankings for further analysis. If ties occur among the top five, all tied system classes are selected. The user must select at least one candidate system class from each of the three major system categories: (1) Astronaut System, (2) System with Manipulator or Prime Vehicle, and (3) System with Manipulator or Auxiliary Vehicle.

STEP IV - The user reviews the development status of each system included in each selected system class. He selects for the final trade-off analysis all systems which are the nearest to operational status. The rationale for this selection is that the cost/effectiveness data on highly developed system will be most accurate and the development costs will be minimal.

STEP V - The user reviews Cost Factor definitions, in Workbook Section 7.0, and selects those factors which are important to the mission he is analyzing.

STEP VI - The user performs the final cost/effectiveness evaluation of all candidate EV systems. In performing this evaluation the user ranks all trade-off items (i.e., performance measures and cost factors) with respect to their importance to the mission (Any number of items may be ranked the same, as long as a numerical, integer-by-integer sequence is used.).

The user reviews the data on each system and rank orders all candidate EV systems with respect to each trade-off item. The ranking is most favorable to least favorable (e.g., the EV system with the lightest weight will be ranked most favorable, with respect to the trade-off item weight, and the one with the heaviest will be ranked the least favorable). Ties on the "favorable-unfavorable" scale are assigned the same number, and mission data on a candidate EV system are given the median rank of all EV systems on that particular trade-off item.

The user multiplies the "favorable-unfavorable" ranking of each candidate system on a given trade-off item by the "importance" ranking of the trade-off item. Once this multiplication is complete across all candidate EV systems for each trade-off item, the products are summed across trade-off items for each system.

In order to determine which systems should be considered as "most adequate" for his mission, the user calculates the range of sums he could expect by chance. He then identifies all EV systems for which the sum is no greater than that of the EV system with the minimum sum plus 10% of the expected range. All systems meeting this criteria are considered equally adequate.

STEP VII (Optional) - In Step VI the user rank orders trade-off items by their "importance." Obviously, the outcome of the evaluation will be influenced by this ranking. Through Step VII the user has an opportunity to evaluate the sensitivity of the EV system selection process to his subjective rankings. Essentially Step VII requires that he re-rank the trade-off items and re-evaluate the EV systems. If the resulting list of "adequate" systems is different from the Step VI original, he should make sure that his rankings are valid; otherwise, the EV systems selected might not be appropriate for his mission.

Finally, Step VII gives the user the opportunity to check the impact of missing data on EV system selection. Essentially, the user re-evaluates the EV systems using three different sets of missing data. In one set, all missing data is assumed "least favorable" on every trade-off item. In the second it is assumed to be "most favorable." Finally, missing data cells receive "most or least favorable" numbers based on a random assignment process. If the result of any re-evaluation is different from that found in Step VI, the user should contact the manufacturer of the EV system for additional data.

7.2.3 Remarks on the PEEVS

The PEEVS workbook was prepared for use early in system development; therefore, it is not intended to identify the optimal EV system. Early in a development cycle, an attempt to select an optimal EV system would probably be frustrated by the lack of mission and prime vehicle design definition. Thus, PEEVS attempts only to eliminate those systems which appear particularly unfavorable for the mission functions. Systems remaining after the completion of the PEEVS evaluation should all remain as candidates until more detailed trade-offs can be performed.

The "favorable-unfavorable" assignment of each EV system class used in Step III should be periodically reviewed or updated as the assignment was made on data that was available prior to 1970.

Obviously, the data included on the data sheets in Section 8.0 of the workbook must be periodically updated.

Since no statistical evaluation was made of the Step VI and VII procedures, no "Significance Tables" could be generated. Also the parameters used in these steps were gross estimates made by the author in order to have a completed evaluation procedure. Thus, these parameters are subject to changes. It should be noted, however, that in all cases parameters and tests were selected to be conservative, i.e., less discriminating between EV system classes. Therefore, the usefulness of PEEVS as an "Eliminator" was not sacrificed.

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APPENDIX A

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APPENDIX B

LIST OF ABBREVIATIONS

MATRIX RESEARCH

ABBREVIATIONS

AAP	Apollo Telescope Mount
AEC	Atomic Energy Commission
AES	Advanced Extravehicular Suit
ALSS	Astronaut Life Support System
AM	Airlock Module
AMF	American Machine and Foundry
AMU	Astronaut Maneuvering Unit
ANC	Argonne National Laboratory
ASMU	Automatic Stabilized Maneuvering Unit
ATM	Apollo Telescope Mount
AV-M	Auxiliary Vehicle - Manned
AV-UM	Auxiliary Vehicle - Unmanned
CM	Command Module
CMG	Control Moment Gyros
CRL	Central Research Laboratory
CR/CS	Cargo Rack/Control Station
ECS	Environment Control Subsystem
ELSS	Extravehicular Life Support System
EMU	Extra Mobility Unit
EOSS	Earth Orbital Space Station
EV	Extravehicular
EVA	Extravehicular Activity
FSAS	Free Space Activity System
FTS	Film Transport System
GATV	Gemini Agena Target Vehicle
G.E.	General Electric Co.
HECMAR	Human Engineering Criteria for Maintenance and Repair
HHMU	Hand Held Maneuvering Unit
IMM	Independent Manned Manipulator
IR	Infra Red
ITMG	Integrated Thermal Meter
IVA	Intravehicluar Activity
IV	Intravehicular
LCG	Liquid Cooled Garment
LTV	Ling-Temco-Vaught
MDA	Multiple Docking Adapter
M/S	Master/Slave
MSFC	Marshall Space Flight Center
MWP	Maneuvering Work Platform
NAR	North American Rockwell

ABBREVIATIONS
(Cont'd)

OPS	Oxygen Purge System
OWS	Orbital Workshop
PECS	Portable Environment Control System
PEEVS	Performance Effectiveness
PGA	Pressure Garment Assembly
PV-M	Prime Vehicle - Manned
PV-UM	Prime Vehicle - Unmanned
RD&E	Research, Development & Engineering
SAS	Space Activity Suit
SERP	Serpentuator
SCHMOO	Space Cargo Handler and Manipulator for Orbital Operations
STEM	Storable Tubular Extendable Member
UV	Ultra Violet
VCM	Ventilation Control Module
WPAFB	Wright Patterson Air Force Base
ZERO G	Zero Gravity ("0-g")

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SELECTION OF SYSTEMS TO PERFORM EXTRAVEHICULAR ACTIVITIES - MAN AND MANIPULATOR - VOLUME 2

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Matrix Research Company

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